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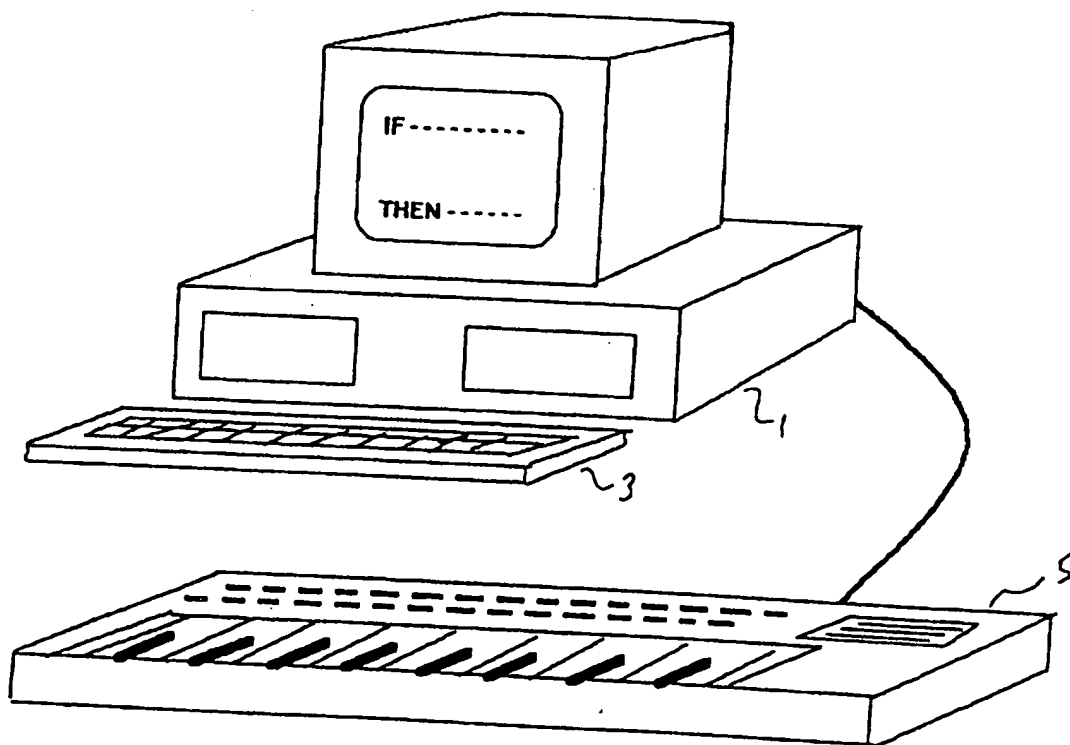
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(54) Title: MUSIC COMPOSITION



(57) Abstract

A music composition system (1), comprising receiving a first harmony including a first melody, analyzing the first harmony to derive in real-time a rule relating the first melody to the first harmony, receiving a second melody, and applying the rule in real-time to the second melody to produce a second harmony relating to the second melody.

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MUSIC COMPOSITIONBackground of the Invention

## 5           1. Field of the Invention

The invention relates to computer-aided music analysis and composition.

## 2. Description of the Prior Art.

Composition and playing of music requires years of  
10 dedication to the cause. Many talented individuals are  
simply unable to dedicate so much of their lives to learning  
the skill. Technology has grappled with allowing non-  
practiced individuals to play music for years. Player  
pianos, automated music and rhythm organs, and electronics  
15 keyboards have minimized the learning curve. While these  
devices automated some parts of music reproduction to some  
extent, they severely constrained creativity.

The player piano, for example, used a predetermined  
program indicated by holes in a roll of paper. The keys  
20 that were pressed based on those holes were indifferent to  
the creative ideas of an unskilled operator.

All of these technologies force operators to rely on  
pre-packaged music originated by others. They allow very  
little creativity. Even the keynote in which the pre-  
25 programmed sounds are to be played is preselected. Merely

arranging snippets of another's music has proved a poor substitute for creating one's own music.

Recently, some have tried to apply computer power in aid of the composer. U.S. Patent no. 5,308,915 is  
5 representative of the many systems that use a neural network. Computer-based music analysis and composition has used, for example, neural network computer technology. Neural networks which make use of concepts related to the operation of the human brain. Neural networks operate in an  
10 analog or continuously variable fashion. Some neural network approaches use some sort of rule-based preprocessing and post-processing. The knowledge which the system uses to make its decisions is inaccessible to the user.

For example, takes a system with the following  
15 steps:

Input from MIDI keyboard (10)

|  
|

Preprocessor puts input into a form that a neural network  
20 can understand (20)

|

Neural network (30)

|

Postprocessor to turn neural network output back into  
MIDI (40)

Output to MIDI sound module (50)

5

The input and output that the system is sending may be understandable at each point in the process. However, ALL of the LEARNED knowledge that the system uses to make its decisions is hidden in the weights of the  
10 connections inside the neural network (30). The inventors recognized that this knowledge is extremely difficult to extract from the network. It is difficult to phrase music in a form directly that can be understood by a network. All neural networks share the common characteristic that at some  
15 point in the process, knowledge is not stored in a directly-accessible declarative form.

Another limitation commonly encountered in neural network approaches is related to external feedback, where the output of the network is used at some point in the  
20 future as input to the network. Here, the analog nature of the network allows it to slide away from the starting point and towards one of the melodies on which it was trained. One example is a network which learned the "blue danube".

The problem with this network was that no matter what input you gave it, eventually it started playing the blue danube. The key point here is that the network may have learned the blue danube, but it did NOT learn HOW to write it or how to  
5 write SIMILAR but not IDENTICAL music.

Moreover, neural networks are analog machines, and it is difficult to make an analog machine (a neural network) approximate a discrete set of data (music with a finite number of pitches and rhythmic positions).

10 One type of network used for composition is a single feed-forward network. This network has been used to associate chords with melodies. This system was described by Shibata in 1991. This system represents chords as their component tones instead of by their figured bass symbols.  
15 The network also required the entire melody at once, meaning it could not be performed in real-time as the melody was being generated by a musician. An important contribution from Shibata's work is the use of psychophysical experiments to gauge the success of a computer compositional approach;  
20 listeners evaluated the output of the network compared to a table-driven harmonizing approach and indicated a measure of how natural the output sounded.

Adding recurrent connections to a neural network provides additional computational complexity, and allows the network to evolve some sense of movement through time. This approach has been used to teach a network a single 153-note  
5 melody.

The inventors recognized certain limitations in these previous studies. Neural networks have a continuous analog nature, which has proven to be difficult to apply to apply to music's a discrete set of events. Almost all music  
10 has some sort of regular rhythm, with notes starting either directly on a beat or at just a simple fraction of the beat. Note durations behave similarly.

Most music is also tonal, using only a finite number of pitch values. Neural networks, which use a continuous or  
15 analog mode of operation, require excessive training to approximate this discrete behavior. This is a very inefficient use of a nueral network.

Neural networks learn in a connective way, which is not conducive to determination of the rationale behind the  
20 learning. The inventors recognized that a music composer either likes or dislikes certain effects which have been obtained. It is an object of the present invention to allow the composer to interact with the computer based learning

system by viewing and/or modifying the results of the computer based learning system. It might be possible to modify a neural network to respond to feedback from a user about what that user likes or dislikes as suggested

5 according to the present invention. Even if this were done, however, it would not be easy to ask the network, "I HATE that! Why did you do that?"

Some research has been done using rule-based computer analyses that learn from examples. Rule-based  
10 systems are inherently discrete, easing system training. An example of a generic rule is shown below, with a left-hand side (LHS) referencing one or more attributes  $A_x$  and a right-hand side (RHS) referencing an attribute  $A_{RHS}$ . Such a rule infers the RHS attribute  $A_{RHS}$ . A set of such rules  
15 is known as a rule base.

LHS	RHS
IF $A_1 = a_{1,2}$ and $A_2 = a_{2,5}$	THEN $A_{RHS} = a_{RHS,3}$

U.S. Patent No. 5,418,325 describes a computer receiving a musical element, i.e., a series of notes over  
20 time. This is used to build a table of rules that indicate which notes are most likely to follow each note received. Such a table is of some help to a composer of a new element



in order to create a series of notes that are pleasing to the ear.

The inventors recognized that this will give a correct distribution, but will not necessarily sound good.  
5 Music which is done purely probabalistically is BORING, i.e., it doesn't interest the ear.

U.S. Patent No. 5,418,323 describes a system in which rules built from a small seed string of notes. The system is usually not responsive to feedback in real-time.

10 The systems of U.S. Patents Nos. 5,302,777, 5,218,153, and 4,981,544, for example, create such competing rules but follow through with only simplistic methods of making use of these rules. The present invention defines a new technique of weighing which allows competing rules to be  
15 maintained and appropriately used.

It is hence an object of the present invention to provide a system which includes all of the advantageous aspects of the present invention - a system which operates using the least possible amount of computer power to learn  
20 musical rules and weights and apply them in real-time. The present invention also allows interaction with the rules, e.g. by viewing and/or modifying the rules that have fired.

The system preferably stores information in the form

of rules, unlike the conventional learning system which stores information. The use of rules in addition to learning provides some of the benefits of both. The present invention uses probabilistic rules to obtain many of the capabilities of analog networks. By so doing, the present invention obtains all of the benefits of a rule-based system. This allows us to ask the system to explain its decisions.

Practical operation of these systems is enhanced if the rule base is appropriately managed. Another aspect of the present invention defines a special real-time dependency pruning system which enhances the accuracy of the rulebase. Another aspect teaches segmenting the rulebases in a way which facilitates their use. Yet another aspect of the invention defines using probabilistic, e.g., not deterministic, rules.

The operating techniques used by the present invention allow a simple algorithm with small chunks of data to accompany a live musician. The preferred system uses special rules which are optimized for the use according to the present invention.

It is therefore an object of the invention to provide a music composition system useful to one lacking

formal training in musical arts. Another object is to provide a system which creates rules through analysis of music. Another object of the system is to provide a real-time composition system which applies these rules in real-time. The present system does not need to create the rules in real-time. In fact, the computers presently being used take several minutes to create the rules it later is able to apply to musical input with a delay of less than 1/10 second.

Another object of the invention is to provide an automated music composition system that creates rules through real-time analysis of music. In addition, it is an object of the invention to provide an automated music composition system requiring little explicitly-coded knowledge of music. It is a further object of the invention to provide an automated rule-based music composition system in which multiple competing rules contribute to an outcome. Still another object of the invention is to provide an automated rule-based music composition system using special rules optimized to provide the best results.

#### Brief Description of the Drawings

These and other aspects of the invention will now be described in detail with reference to the accompanying drawings, wherein:

Fig. 1 is a diagram of hardware equipment  
5 connections according to the invention;

Fig. 2 is an overall flowchart of a method of music composition according to the invention;

Fig. 3 is a flowchart of a method of conversion to figured bass according to the invention;

10 Fig. 4 shows a formula which determines a J-measure according to the invention;

Figs. 5-8 depict a detailed flowchart of a method of rule generation according to the invention;

Fig. 9 is a flowchart of a method of harmonization  
15 according to the invention;

Fig. 10 is a flowchart of a method of conversion to MIDI according to the invention; and

Figs. 11-14 are musical charts representing products of music composition according to the invention.

## 20 Description of the Preferred Embodiments

It should be understood that many of the techniques described herein are intended to be carried out in software

on a computer-based system, such as a personal computer or synthesizer. The following describes the functions that are carried out.

The music composition system of the present  
5 invention automatically learns rules representing a particular style of music and uses those rules to generate new music in the same style. The generated accompaniment can be for a performing musician in real-time.

Fig. 1 shows the system using a standard 486SX  
10 computer 10 running a standard operating system, e.g., DOS or a multithreaded operating system such as Microsoft Windows NT. User input in, e.g., MIDI format can be accepted through the computer keyboard 30 or through any synthesizer or musical keyboard connected to the computer by  
15 a standard MIDI interface. The system's output is sent via the MIDI interface to a synthesizer 50 for playback.

The application examples below provide a context for the detailed information to follow. For instance, the system can operate as a computerized expert trained using  
20 examples of a particular musical style. Students attempting to write music in the particular style can ask the computerized expert not only to check their compositions for errors but also to suggest alternatives. Because the system

is rule-based, the computerized expert based on the system can also provide explanations showing why the suggestions overcome the errors.

The system can also allow comparison of two or more  
5 different composers' works by generating a rule base for each composer. Furthermore, a musical piece can be checked against a particular composer's known rule base to determine whether the piece was in fact authored by that composer.

Soundtracks can be generated using the system. The  
10 system creates rule bases, i.e. is trained, from musical pieces known to provoke certain feelings or having certain styles. These rule bases can be used subsequently to generate music appropriate for particular situations.

The system can make a small number of musicians  
15 sound like a large orchestra. For example, additional musical lines generated from an existing four- or five-part harmony can be fed to the synthesizer to make a string quartet sound like an entire string orchestra.

Along the same lines, the system can simulate a  
20 rock-n-roll band, allowing an aspiring musician to play along. With the aspiring musician's musical instrument plugged into the computer and the style of each member of, say, The Beatles musical group encoded into an individual

rule base, the system can accompany the aspiring musician in much the same way as The Beatles would have. Furthermore, trained on a missing member's style, the system can take the place of that member in a musical group's subsequent  
5 recordings.

The system is capable of learning all of its musical knowledge from sample pieces of music. This capability provides flexibility, allowing application of the system to musical styles not originally planned. In addition, because  
10 the rules are determined and applied automatically, requiring no hand-tuning, the system works well for users lacking much technical knowledge of music. Finally, able to accept industry-standard MIDI song files as musical input, the system can generate, quickly and easily, series of rule  
15 bases representing the styles of various composers. Control over rule generation is available for advanced users of the system.

A particularly useful feature of the system is its ability to demonstrate the basis of its decisions by listing  
20 the rules extracted during training. Such listings make the system useful as an interactive aid for teaching music theory and as a tool for historians attempting to understand the creative processes of composers such as Bach and Mozart.

A further indication of the system's power is its ability to resolve conflicts when two or more rules call for different outcomes. The system employs several such schemes, including rule weighing and real-time dependency  
5 pruning.

The present invention provides efficient ways of generating and activating, or firing, rules, allowing the system to operate in real-time using everyday computers. Thus any live musician can use the system to generate  
10 accompaniment. The real-time aspect of the system also fits well with other interactive tasks, such as teaching music theory.

An example of the system's work is shown below. Using the well-known Bach chorales as input, the system  
15 generates the five rules below, which are some of the most commonly-used rules in classical Bach harmony, typically appearing in any first-year music theory textbook.

1. IF Melody0 E THEN Function0 1  
AND Function1 V  
20 (G Major to C Major)

2. IF Melody0 F THEN Function0 IV



AND Function1 V  
(G Major to F Major)

3. IF Function1 V THEN Inversion0 I1  
AND Function0 IV

5 4. IF Function1 V THEN Inversion0 I0  
AND Function0 I

5. IF Function0 vii07 THEN Inversion0 I1

The system does not use a textbook but learns such rules on its own, as explained below.

10 Fig. 2 is a flowchart showing the operation of the system. The flowchart shows the overall operation, including:

Conversion to figured bass (step 1000),  
Generation of example tables (step 1010),  
15 Derivation of rules from examples (step 1020),  
Filtering and segmentation of rules (step 1030),  
Subsumption pruning of rules (step 1040),  
Generation of dependence data (step 1050),  
Harmonization using rules (step 1060), and

## Conversion to MIDI (step 1070).

The preferred system works with musical information represented in a variation of a form known as figured bass. The figured bass form has been used frequently by composers to present a piece's harmonic information without stating the precise location, duration, and pitch for every single note. In classical form, a figured bass states the melody and represents the underlying harmony as a series of chords. Each chord is specified by its function in the key of the piece of music, written as a Roman numeral or "figure," and the pitch which is being played by the bass voice. There are usually several ways of voicing any given figure, i.e., turning the figured bass representation back into notes. The preferred system uses an extended form of figured bass that includes the chord notes played by all the voices, which allows the system to turn the figured bass back into notes while playing.

## - Conversion to figured bass

The conversion step 1000 converts music represented in MIDI file format into the figured bass format needed by the steps that follow. The MIDI file format is a

specification for storage and transmission of musical data. Under MIDI, musical data is arranged as a stream of events occurring at specified intervals. The following is a typical stream of MIDI data:

```

5  Header format=0 ntrks=1 division=240
   Track start
   Delta time=0 Time signature=3/4 MIDI-clocks/click=24 32nd
     notes/24-MIDI-clocks=8
   Delta time=0 Tempo, microseconds-per-MIDI-quarter-note=41248
10  Delta time=0 Meta Text, type=0x01 (Text Event) leng=23
     Text = <Chorale #001 in G Major>
   Delta time=480 Note on, chan=1 pitch=67 vol=88
   Delta time=0 Note on, chan=2 pitch=62 vol=72
   Delta time=0 Note on, chan=3 pitch=59 vol=88
15  Delta time=240 Note off, chan=4 pitch=43 vol=64
   Delta time=0 Note off, chan=3 pitch=59 vol=64
   Delta time=0 Note off, chan=2 pitch=62 vol=64
   Delta time=0 Note off, chan=1 pitch=67 vol=64
   Delta time=0 Note on, chan=1 pitch=67 vol=81
20  Delta time=0 Note on, chan=2 pitch=62 vol=75
   Delta time=0 Note on, chan=3 pitch=59 vol=88
   Delta time=0 Note on, chan=4 pitch=55 vol=60
   Delta time=240 Note off, chan=4 pitch=55 vol=64
   Delta time=0 Note off, chan=3 pitch=59 vol=64
25  Delta time=0 Note off, chan=2 pitch=62 vol=64
   Delta time=0 Note on, chan=2 pitch=64 vol=58
   Delta time=0 Note on, chan=3 pitch=60 vol=78
   Delta time=1920 Meta Text, type=0x01 (Text Event) leng=7
     Text = <Fermata>

```

30           Each line in the stream is an event. For example, in the line "Delta time=240 Note off, chan=4 pitch=43 vol=64," the phrase "Delta time=240" means that the line starts executing 240 MIDI-clocks of time after the last line

started executing. "Note off" indicates that the note presently being played by channel, i.e., voice "4" is to be turned off.

The significant events in the sample data are listed  
5 in the following table.

Event	Function	Relevant Parameters	Meaning
Time signature	Gives information about the timing of the piece	Time signature	Needed to convert beats into measures and to determine beat accents.
		32nd-notes/24-MIDI-clocks	Needed to convert current time into beat number.
10 Note on/Note off	Turns a note on or off for a specific voice	Channel	Which voice is changing (1=soprano, 2=alto, 3=tenor, 4=bass).
		Pitch	Which note is changing (pitch=60 is middle C <sup>3</sup> ).
Meta Text	Allows arbitrary messages to be sent	Text	"Chorale #001 in G Major" gives the name and key of the piece. "Fermata" states that there is a fermata on the chord starting at that time.

The inventors prefer using musical data that is not in the MIDI format as their input for musical analysis. In MIDI data, which notes are being played at a given point in time is difficult to determine because the durations of the notes are not explicitly coded. Rhythmic structure is difficult to determine as well. The MIDI format is sensitive to the exact notes being played. For example, transposing the piece, i.e., adding a fixed pitch interval to all notes, changes every pitch in the music's MIDI data stream. If a piece is transposed up a semitone (from C to C-sharp, for example), every single pitch in the MIDI data changes. Even minor changes in the voicing of a chord have radically different representations in the MIDI data. For example, a C Major chord (C, E, G, C) could have pitches {60, 64, 79, 84}, or {67, 72, 76, 84}. The two voicings sound almost identical and have similar functions, but share only one common pitch. This problem is solved by transforming the data into a figured bass format.

The figured bass format used by the system more concisely states the harmonic content and rhythmic information for an accompaniment. In figured bass format as opposed to MIDI format, music is organized in terms of chords and beats instead of individual transition events. A

typical figured bass corresponding to the first few chords of MIDI data listed above, follows.

	MEL	FUNC	IN	TP	AP	SP	DUR	ACC
5	C	I	I0	T1	A2	S0	2	un
	C	I	I0	T0	A1	S0	2	acc
	C	IV	I1	T0	A1	S2	1	un
	C	vi	I0	T2	A0	s1	1	n
10	G	V	I1	T2	A0	S0	2	un
	E	I	I0	T0	A2	S1	2	ACC
	E	iii	I1	T2	A1	S0	1	un
	D	V	I0	T1	A0	S2	1	n
15	C	vi	I0	T1	A2	S1	2	un
	C	IV	I0	T0	A1	S2	1	ACC
	C	-	-	-	-	-	1	n
	C	-	I3	T0	A1	S2	1	un
20	D	vii07	I1	T2	A0	S1	1	n
	E	I	I0	T2	A0	S1	2	un
	D	V	I0	T0	A1	S2	4	FERM

The first column, with the heading MEL, lists the pitch played by the soprano, which is the melody note of the piece. Next is the column headed FUNC, which is the chord function or figure. The most common functions in a major key in the work of Bach, for example, are listed in the following function table, which is only a subset of the total list of functions used by the system.

	<u>Function</u>	<u>Chord Name</u>	<u>Pitches</u>
	I	C Major	C, E, G
	I7	C7	C, E, G, B-flat
	ii	D minor	D, F, A
5	V/V	D Major	D, F-sharp, A
	iii	E minor	E, G, B
	V/vi	E Major	E, G-sharp, B
	IV	F Major	F, A, C
	V	G Major	G, B, D
10	V7	G7	G, B, D, F-sharp
	vi	A minor	A, C, E
	vii07	B diminished 7th	B, D, F, A-flat

The middle set of four columns, headed IN, TP, AP, and SP, indicate the positions, respectively, of the bass voice, or inversion; the tenor voice; the alto voice; and the soprano voice. The positions are numbered from 0 to 3, wherein 0 indicates the first pitch listed in the function table above and 3 indicates the fourth pitch. For example, again using the function table above, in the key of C major, a V7 chord with positions I0 T1 A3 S0 would contain, in order, the pitches G, B, F-sharp, and G. Use of this position notation provides the system with musical data that, while allowing easy reconstruction of the original pitches, is key-independent, because if a piece of music is transposed, its voice positions remain unchanged.

In addition, since figured bass reduces the number of possibilities from twelve pitches to four positions, the overall complexity of the set of musical data is reduced.

The next column, under the heading DUR, shows the  
5 duration of the particular chord. Lastly, the column headed ACC also indicates a timebase, by displaying the accent to be placed upon the chord. Under the ACC column, the following notations have the following meanings: "FERM", standing for fermata or held chord, indicates the strongest  
10 accent; "ACC" signals that the chord begins at the start of an accented beat; "un" specifies that the chord begins on an unaccented beat; and "n" means that the chord does not begin at the start of a beat.

Fig. 3 shows converting a musical piece described in  
15 a MIDI file to the desired figured bass form. The system scans through the MIDI file and assembles all of the pieces together to determine which notes are being played by the voices, viz, bass, tenor, alto, soprano, and at which times (step 1000a). The system then extracts the key of the piece  
20 from the initial MIDI text event, an example of which is shown in the sample MIDI stream above (step 1000b). Standardizing to simplify later analysis and to ease comparisons of different pieces, the system transposes the



piece to the key of C Major, with all of the pitches changing appropriately (step 1000c). Next, beginning a new chord whenever a voice changes pitch, the system segments the piece into chords (step 1000d).

5                    Segmented into chords, the piece appears as follows.

	TIME	DUR	B	T	A	S
	000					
	004	2	{ C3	E4	G4	C5 }
	006					
10	006	2	{ C4	E4	G4	C5 }
	008	1	{ A3	F4	A4	C5 }
	009	1	{ A3	E4	A4	C5 }
	010	2	{ B3	D4	G4	G5 }

Representing one timestep, i.e., one-eighth of a  
 15 note, and one chord, each line contains information about when the chord was started, its duration, and which note is being played in each voice. Next, determining the melody pitch by taking the soprano note without the octave, the system also determines the accent of each chord (step  
 20 1000e). The accent is based on the time a chord starts and the time signature of the piece. For example, in 3:4 time, the time signature for the sample listed above, a measure is 6 timesteps long because each timestep is one-eighth of a note. Thus, accented beats occur every 6 timesteps and  
 25 unaccented beats occur every 2 timesteps, as indicated in

the table below, wherein  $n$  is an integer representing the measure number.

	<u>Time</u>	<u>Accent</u>						
	6n+0	ACC						
5	6n+1	n						
	6n+2	un						
	6n+3	n						
	6n+4	un						
	6n+5	n						
10	<hr/>							
	TIME	DUR	B	T	A	S	MEL	ACC
	000	-----						
	004	2	{	C3	E4	G4	C5	} C un
	006	-----						
15	006	2	{	C4	E4	G4	C5	} C ACC
	008	1	{	A3	F4	A4	C5	} C un
	009	1	{	A3	E4	A4	C5	} C n
	010	2	{	B3	D4	G4	G5	} G un

Next, the system identifies a timestep with a particular known chord by attempting to match the information at each timestep with a known chord, i.e., matching if all pitches being played could be part of that known chord (step 1000f). For example, using the table above and a list of 120 common chords sufficient to identify 99% of all chords occurring in Bach's music, the chord at timestep=8 is identified as an F Major chord because all of its pitches are either F, A, or C. A chord unable to be identified as a known chord is marked as such, because such

a chord is usually the product of a passing tone or other ornament and has no significant function in the piece.

Updated, the table then appears as follows.

	TIME	DUR	B	T	A	S	MEL	ACC	RT	TYPE
5	000									
	004	2	{	C3	E4	G4	C5 }	C	un	C
	006									Major
	006	2	{	C4	E4	G4	C5 }	C	ACC	C
	008	1	{	A3	F4	A4	C5 }	C	un	F
10	009	1	{	A3	E4	A4	C5 }	C	n	A
	010	2	{	B3	D4	G4	G5 }	G	un	G
										Major

Next, the system determines the position of each voice by comparing the pitch of each voice with the pitches allowed in the identified known chord (step 1000g). Thus, in the current example, the chord at timestep=8 has pitches {A, F, A, C}, which correspond to positions {I1, T0, A1, A2}, resulting in the following determinations of voice positions.

TIME	DUR	B	T	A	S	MEL	ACC	RT	TYPE	IN	TP	AP	SP	
20000														
004	2	{	C3	E4	G4	C5 }	C	un	C	Major	I0	T1	A2	S0
006														
006	2	{	C4	E4	G4	C5 }	C	ACC	C	Major	I0	T1	A2	S0
008	1	{	A3	F4	A4	C5 }	C	un	F	Major	I1	T0	A1	S2
25009	1	{	A3	E4	A4	C5 }	C	n	A	Minor	I0	T2	A0	S1
010	2	{	B3	D4	G4	G5 }	G	un	G	Major	I1	T2	A0	S0

Now the system identifies a function associated with each chord, by comparing the root and type of each chord

with a table of common functions such as the Bach-related one described above. (step 1000h). When a chord is unable to be matched with any of the common functions, its function is marked as unknown, indicating that the chord may be the result of an ornament serving no harmonic function.

Finally, since not needed in the figured bass notation, information about absolute time and voice pitch is discarded, leaving the following as the output of the conversion from MIDI to figured bass (step 1000i).

10	MEL	FUNC	IN	TP	AP	SP	DUR	ACC
	C	I	I0	T1	A2	S0	2	un
	C	I	I0	T1	A2	S0	2	ACC
15	C	IV	I1	T0	A1	S2	1	un
	C	vi	I0	T2	A0	S1	1	n
	G	V	I1	T2	A0	S0	2	un

In addition to the chord-based conversion just described, the system can use beat-based conversion. Beat-based conversion takes advantage of harmonic functions usually changing only minimally between beats, not within a single beat. Ornaments usually relate to only half of a beat and the chords formed from them are less correlated with the surrounding music than the chords relating to the other half of the beat. The examples which include

information from ornament chords tend not to correlate well with other examples and thus produce only weak rules.

The beat-based conversion method is more complex than the chord-based method because beat-based conversion  
 5 examines each chord which is part of a beat and generates an example assuming that the chord was the significant chord for that beat. All examples for a timestep then have their weights normalized so that the total weight for each timestep is one. The segment of figured bass listed above  
 10 would produce the following examples.

	%NAME 0	Weight	
	%NAME 1	Function1	
	%NAME 2	Function0	
	1.0	-	I
15	1.0	I	I
	0.5	I	IV
	0.5	I	vi
	0.5	IV	V
	0.5	vi	V

20 This is fairly straightforward when the examples are using only one previous beat of data. However, if an example set is built from the current beat and four previous beats, and each beat has two chords, i.e., an ornament chord and the real chord, then each beat results in a quantity of samples  
 25 equal to 2 raised to the fifth power, i.e., 32 examples, each with weight 0.03125. Therefore, excepting example sets with only a small time window, a beat-based example set uses

a great deal more memory than a standard chord-based example set.

#### - Generation of example tables

Rules are generated based on examples that are  
 5 created from the figured bass data. Each example includes  
 the data necessary to agree or disagree with a potential  
 rule, including information about previous timesteps.  
 Examples in the table can also be weighted, so that they can  
 count for more or less than a normal example. As indicated  
 10 below in the following illustrative table, some examples  
 have double the weight of other examples. Each example  
 includes information about the melody and chord function  
 used at the current timestep and at the previous two  
 timesteps.

15	%NAME	0	WEIGHT						
	%NAME	1	Duration0						
	%NAME	2	Melody2						
	%NAME	3	Melody1						
	%NAME	4	Melody0						
20	%NAME	5	Function2						
	%NAME	6	Function1						
	%NAME	7	Function0						
	1.0	1	C	C	C	I	I	IV	
	1.0	1	C	C	C	I	I	vi	
25	1.0	2	C	C	G	I	IV	V	

	1.0	2	C	C	G	I	vi	V
	1.0	2	C	G	E	IV	V	I
	1.0	2	C	G	E	vi	V	I
	1.0	1	G	E	E	V	I	iii
5	1.0	1	G	E	D	V	I	V
	1.0	2	E	E	C	I	iii	vi
	1.0	2	E	D	C	I	V	vi
	0.5	1	E	C	C	iii	vi	IV
	0.5	1	D	C	C	V	vi	IV
10	0.5	1	C	C	D	vi	IV	vii07
	0.5	2	C	D	E	IV	vii07	I
	1.0	4	D	E	D	vii07	I	V

To generate examples from a figured bass, the system moves a window down the list of chords, copying only certain pieces of information at each timestep. For instance, working with the sample figured bass conversion output data above to generate an example table using fields Function0 and Function1, i.e., the chord functions at the current and previous timestep, respectively, the system would produce the following. Each line is an example containing the attributes Function1 and Function0.

	Function1	Function0
	-	I
	I	I
25	I	IV
	IV	vi
	vi	V

- Derivation of rules from example tables

While generating rules from examples, the system uses a J-measure defined as shown in Fig. 4.

The J-measure represents a balance of the amount of information a rule contains and the probability that the rule will be able to be used. Since a rule is less valuable if it contains little information, the J-measure is low when the rule's probability of being correct is low, i.e., when  $p(x|y)$  is about the same as  $p(x)$ . A rule which fires only extremely rarely is of minimal use even if it is extremely conclusive. For instance, a rule base containing many always-correct rules, each useful on only one example, tends to perform extremely well on a training set but dismally in general.

An important part of the present invention is the generation technique that is used herein. The technique includes sorting the examples before extracting the rules therefrom. This has greatly improved the speed of the technique, as described herein.

Rules are generated using preset parameters which can be modified by the user if necessary. To prevent generation of rules based on too few examples, the system uses a parameter  $N_{\min}$  which denotes the minimum number of examples with which a rule should agree.



A list of examples  $E_1, E_2, \dots, E_{NEX}$  is used to generate the rules. The value of attribute  $i$  for example  $E_j$  is denoted  $e_{j,i}$ .

Each rule generated preferably has a minimum J-measure  $J_{min}$  and fires correctly a minimum fraction of the time  $p_{min}$ .

On the output or right-hand side of the rule, the rule that is generated infers an attribute  $A_{RHS}$  taking integer values  $a_{RHS,1}, a_{RHS,2}, \dots, a_{RHS,NRHSV}$ , where  $NRHSV$  stands for the number of possible RHS values. Similarly, the attributes allowed on the input or left-hand side of the rule,  $A_1, A_2, \dots, A_{NLHS}$ , take on  $|A_i|$  integer values  $a_{i,1}, a_{i,2}, \dots, a_{i,NLHSV}$ .

The complexity of the system is reduced using a maximum rule order  $O_{max}$ , representing the maximum number of attributes allowed on the left-hand side.

The system uses an array  $NR$  of size  $NRHSV$ , as described herein.

The processing according to the present invention uses substeps (Figs. 5-8) for each possible combination of LHS attributes (steps 1020a-b). The system adds a hash column  $H$  to the table, each element  $h_i$  of which is preferably a signed 32-bit integer corresponding to an

example  $E_i$  (step 1020c). Of course, more detailed calculations would require more bits. Using a combination of LHS attributes  $A_1, A_2, A_5$ , for instance,  $h_i$  is determined as follows (steps 1020d-h).

$$5 \quad h_i = e_{i,5} + |A_5| (e_{i,2} + |A_2| (e_{i,1})) \quad (\text{step 1020g})$$

When an attribute is unknown,  $h_i$  is set to -1 (step 1020h).

Next, the system adds a column X of indices to the table:  $x_i = i$  (step 1020i). The table is quicksorted to group the lines of the table by hash value (step 1020j).

10 Column X is actually what is sorted, because each entry in column X is only a two-byte integer. The index is only a 2-byte integer if fewer than 65535 examples are being classified. Otherwise, a 4-byte integer is preferably used. This saves on the amount of memory moved during the sort,  
15 which in turn saves time.

After sorting, the system then searches down the table to generate a preliminary rule for each hash value (steps 1020k-l). The elements of array NR, denoting all possible RHS values  $a_{RHS}$ , are used to indicate correspondence  
20 between RHS values  $a_{RHS}$  and hash values  $h$ . Array element  $NR[a_{RHS,j}]$  is incremented when the hash value  $h_j$  for the current line is the same as the hash value  $h$  for the previous line (steps 1020m-n). If the two hash values are

different, the system notes a preliminary rule relating to the previous hash value and then sets all element arrays NR to zero except for  $NR[a_{RHS,j}]$  which is set to one.

The preliminary rules linking each hash value to one  
5 or more  $a_{RHS}$  are subjected to a series of tests using the parameters mentioned above (steps 1020o-s). A preliminary rule is rejected if the number of examples corresponding to the hash value is less than  $N_{min}$  (step 1020r) or if the particular  $a_{RHS}$  did not occur in more than  $p_{min}$  of the  
10 examples corresponding to the hash value (step 1020q). Finally, the system retains the rule only if its J-measure is above a J-threshold (step 1020s).

Rules are stored in a rule array (step 1020t). The rule array has a certain size, so it can only hold a  
15 predetermined number of rules. If the rule array overflows when a new rule is added (step 1020u), the system drops the rule with the lowest J-measure, which becomes the new J-threshold (step 1020v). After all examples in the table have been considered, the result is a rule base for the  
20 selected attribute.

The following is a simplified illustration further explaining the derivation of rules and using the example table and parameters listed below.

	Attr1	Attr2	Attr3
	-----		
	A	A	B
	A	B	C
5	C	B	C
	C	A	B
	A	B	C
	B	B	C
	C	C	A
10	B	A	C

In this illustration,  $N_{\min}$  is set to 2, which means that a rule which correctly predicts only one example is discarded. The attribute values are found by reading across each example, e.g.,  $e_{2,1}=A$ ,  $e_{2,2}=B$ ,  $e_{3,3}=C$ . The minimum J-

15 measure is 0.001 and the minimum fraction of the time a rule should be correct is  $p_{\min}=0.50$ , i.e., a rule should be right half the time.

In this case, Attr3 is to be predicted using Attr1 and Attr2. In other words,  $A_{\text{RHS}}$  is Attr3, taking on values

20  $a_{\text{RHS},1}=A$ ,  $a_{\text{RHS},2}=B$ ,  $a_{\text{RHS},3}=C$ , because, in this example, Attr1 and Attr2 also have the same possible values A,B,C. Since there are 3 possible values for each attribute,  $|\text{Attr1}| = |\text{Attr2}| = |\text{Attr3}| = 3$ . When dealing with the attribute values as numbers, the following are used: A=0, B=1, C=2. The maximum

25 rule order  $O_{\max}$  being 2, rules can appear in either of the following two forms.

(1st order rule)                    If (term1) then (term2)  
(2nd order rule)                   If (term1) and (term2) then (term3)

First, the system produces hash values for the first-order rules which are of the following form.

5                    If Attr1=(something) then Attr3=(something)

The first column in the table is an index identifying the particular example line.

	1.	A	A	B	hash=0
	2.	A	B	C	hash=0
10	3.	C	B	C	hash=2
	4.	C	A	B	hash=2
	5.	A	B	C	hash=0
	6.	B	B	C	hash=1
	7.	C	C	A	hash=2
15	8.	B	A	C	hash=1

Sorting the examples based on hash value produces the following list.

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	1.	A	A	B	hash=0
	2.	A	B	C	hash=0
	5.	A	B	C	hash=0
	6.	B	B	C	hash=1
5	8.	B	A	C	hash=1
	3.	C	B	C	hash=2
	4.	C	A	B	hash=2
	7.	C	C	A	hash=2

The system will try to make a rule for the examples  
10 with hash=0. This will provide the following possible  
rules.

If Attr1=A then Attr3=B (correct 33% of the time)

If Attr1=A then Attr3=C (correct 67% of the time)

The first of the two rules is discarded because 33%,  
15 or 0.33 as a fraction, is less than 0.50, the minimum  
probability  $p_{\min}$  allowed for a rule to be retained.  
Proceeding similarly for the hash values 1 and 2 provides  
the following retainable rules.

If Attr1=A then Attr3=C (correct 67% of the time)

If Attr1=B then Attr3=C (correct 100% of the time)

Next, generating the hash value based on Attr2 instead of Attr1 produces the following list.

	1.	A	A	B	hash=0
5	4.	C	A	B	hash=0
	8.	B	A	C	hash=0
	2.	A	B	C	hash=1
	3.	C	B	C	hash=1
	5.	A	B	C	hash=1
10	6.	B	B	C	hash=1
	7.	C	C	A	hash=2

The following rules would be retained.

If Attr2=A then Attr3=B (correct 67% of the time)

If Attr2=B then Attr3=C (correct 100% of the time)

15           On the other hand, the following rule is correct sufficiently often but still needs to be discarded because it has only one supporting example, #7, and thus fails to satisfy the  $N_{\min}$  threshold.

If Attr2=C then Attr3=A (correct 100% of the time)

The retained rule list now appears as follows.

If Attr1=A then Attr3=C (correct 67% of the time)

If Attr1=B then Attr3=C (correct 100% of the time)

5 If Attr2=A then Attr3=B (correct 67% of the time)

If Attr2=B then Attr3=C (correct 100% of the time)

Next are the rules which use both Attr1 and Attr2.

In this case, since Attr2 has 3 possible values, the hash value for an example is calculated by the following  
10 equation, producing the table below.

$$\text{hash} = 3 * (\text{Attr1's value}) + (\text{Attr2's value})$$

1.	A	A	B	hash= 3*0+0 = 0
2.	A	B	C	hash= 3*0+1 = 1
5.	A	B	C	hash= 3*0+1 = 1
15 8.	B	A	C	hash= 3*1+0 = 3
6.	B	B	C	hash= 3*1+1 = 4
4.	C	A	B	hash= 3*2+0 = 6
3.	C	B	C	hash= 3*2+1 = 7



7.    C       C       A       hash=  $3*2+2 = 8$

The only rule that is retained from this hash array using the criteria is the following, because no other hash value corresponds to a sufficient number of examples.

- 5    If Attr1=A and Attr2=B then Attr3=C (correct 100% of the time)

The resulting fully updated rule base appears as follows.

- If Attr1=A then Attr3=C (correct 67% of the time)
- 10   If Attr1=B then Attr3=C (correct 100% of the time)
- If Attr2=A then Attr3=B (correct 67% of the time)
- If Attr2=B then Attr3=C (correct 100% of the time)
- If Attr1=A and Attr2=B then Attr3=C (correct 100% of the time)

- 15        This procedure result in a rulebase. Computationally, this algorithm is very appealing because of its simplicity. Each set of LHS values is considered only once. At the time of consideration, all examples with that LHS are

consecutive, so it is not necessary to search through the entire example set to determine the number of examples with which a potential rule agrees. Memory consumption is also reasonable, scaling linearly with the number of examples.

5           - Filtering and segmentation of rules

The rule bases are preferably filtered and/ or segmented to form multiple more efficient rule bases. When it is known that a certain attribute is crucial to determining the RHS value for the rule base, filtering is  
10 used to force all rules contained therein to use that attribute. For example, the system has been used to filter out rules which disregard the current melody note in determining the current chord function.

Segmentation is done when filtering a rulebase would  
15 reduce the domain which the rulebase covers. As in filtering, rules are grouped based on the presence or absence of an attribute on their LHS. However, the rules lacking the desired attribute are placed in a second rulebase, rather than being removed. When a series of  
20 segmented rulebases is used to inference a result, the rulebase with the desired attribute is tried first. If no rules in that rulebase can fire, the rulebase lacking the

desired attribute is tested. This gives the benefits of filtering since rules with the desired attribute are not overwhelmed by rules lacking the attribute. However, unlike filtering, this technique does not involve a loss of domain size, since the less desirable rules are not deleted, just prevented from firing unless there is no alternative).

- Subsumption pruning of rules

After being filtered or segmented, a rule base might still contain many rules that contribute nothing, or contribute so little that they are not worth keeping. Subsumption pruning removes such unneeded rules using the technique described herein.

At step 500, rules are reviewed to determine whether two rules A and B predict the same RHS attribute and value. If so, rule B is removed from the rule base if

- (1) the left-hand side of rule B has more attributes than the left-hand side of rule A,
- (2) every attribute on the left-hand side of rule A is present and has the same value on the left-hand side of rule B, and
- (3) rule A is correct at least as often as rule B.

Since rule B adds no new information in this case, the system becomes more efficient by removing such a rule.

Subsumption pruning should be done after any filtering and segmentation. If rule A in the previous example were  
5 filtered out, then, in retrospect, rule B should not have been removed: we have lost information.

- Generation of dependence data

For the rule-based system to work properly, all rules which are allowed to fire should be independent of  
10 each other. Otherwise, one good rule could be overwhelmed by the combined weight of twenty mediocre but virtually identical rules. To prevent this problem, each rule base is analyzed to determine which rules are dependent with other rules in the same rule base. Two rules are considered  
15 dependent if both rules fire in more than half of the examples that cause at least one of them to fire.

To allow real-time independence pruning, the system maintains for each rule a list of dependent rules with lower J-measures. Independence pruning should be done in real-  
20 time, because removing all dependent rules at the time of rule base creation degrades its quality. For instance, if a

rule base contains only the following two rules which are dependent and the value for  $A_1$  is currently unknown, the system cannot inference a value for  $A$  at all without the second rule.

5            IF  $A_1 = a_{1,2}$  THEN  $A_{RHS} = a_{RHS,3}$  with J-measure 0.013

            IF  $A_2 = a_{2,5}$  THEN  $A_{RHS} = a_{RHS,3}$  with J-measure 0.009

            Given a group of dependent rules, real-time independence pruning prevents the firing of all but the rule with the highest J-measure. The system uses an array  $F$  with  
 10 all values  $f$  initially set to zero, indicating at first that all rules are allowed to fire. When a rule  $R_i$  fires while the system is checking rules in order of decreasing J-measure, the system adds the weight of rule  $R_i$  to the overall weight of the RHS value and then sets to non-zero  
 15 the values  $f_j$  for all rules  $R_j$  dependent with rule  $R_i$ .

            More specifically, the operation proceeds as follows.

1. Consider two rules  $RA$  and  $RB$  which predict the same RHS and value.
- 20 2. Let  $A$  be the set of examples for which rule  $RA$  fires.
3. Let  $B$  be the set of examples for which rule  $RB$  fires.

4. Define the overlap OAB as the number of examples for which both RA and RB fire, divided by the number of examples for which either RA or RB fires.

5. If  $OAB > 0.5$ , the rules are dependent.

5 Each rule is associated with a list of lower J-measure rules which are dependent with the rule. This list is used in real time independence pruning as described herein.

It would seem at first that it would be easiest to  
10 remove all dependent rules at the time a rulebase is created. However, this actually degrades the quality of the rulebase. As an example, assume a rulebase containing only the following two rules, and assume the rules are dependent:

IF A1 = a1,2 THEN ARHS = aRHS,3 with J-measure  
15 0.013

IF A2 = a2,5 THEN ARHS = aRHS,3 with J-measure  
0.009

Now assume we are trying to inference ARHS and that the value of A1 is currently unknown. Only the second rule  
20 would be able to fire. However, if we removed the second rule at the time of rulebase creation, no rules would be able to fire and we would not be able to inference a value

for A. We can avoid this problem by only independence pruning those rules which can fire for a given LHS.

- Rulebase interaction

5 An important part of musical composition is the ability to reinforce good sounds, and prevent bad sounds. Interaction buttons 60 facilitate this operation. The interaction buttons allow the contents of the rulebase to be modified based on whether the user likes or does not like a certain thing that the computer has done.

10 For example, if the computer makes a chord which is not pleasing the user's ear, it indicates that the rules governing that chord are not desirable. The user can press the "bad computer" button, which then adjusts the weight and/or the J-measure for that rule governing the last chord  
15 that was produced. That makes it less likely that the rule will be used subsequently. The opposite is also true - a particularly good sound can be made more likely to recur by initiating the "good computer" button.

20 The system operates by firing rules which have certain weights. The weights are initially assigned by the learning algorithm, based on how well the rules perform (rules which are able to fire frequently or which are right more of the time are given higher weights).

In addition to input through the MIDI keyboard, the user is also given access to two buttons. These buttons are labelled "good computer" and "bad computer", and are pressed when the user either likes or dislikes what the system is  
5 doing.

At any point, the user can press one of the buttons. These buttons affect the weights of the rules which fired to produce the notes generated by the system immediately preceding the button press.

10 When the "good computer" button is pressed, all the rules which predicted (voted for) the system's actual output have their weights increased. The weights can either be increased by a fixed value (for example, each rule which fired might have its weight increased by 0.01), or they can  
15 be increased by a fixed fraction (for example, each rule which fired might have its weight multiplied by 1.01).

Similarly, the "bad computer" button decreases the weights of all rules which contributed to the output which the user did not like.

20 For example, assume for a given timestep the following rules fire:

1. If A then B (weight 0.50)
2. If A then C (weight 0.40)



And let's say that the system picked B as the output of the system.

— If the user hit the "good computer" button, we would increase the weight for rule 1 (say, to 0.51), since the  
5 user liked what that rule predicted.

If the user hit the "bad computer" button, we would decrease the weight for rule 1 (say, to 0.49), so that the system is less likely in the future to do what the user didn't like.

10 Subsumption pruning takes place during rule generation, which is when the system applies a series of rule bases to a melody to fill in a figured bass (Fig. 9). When a rule base is used to infer a RHS value during rule generation, each rule in the rule base is checked in order  
15 of decreasing J-measure (step 1060a). If a rule's dependence value  $f$  is zero and all of the attributes on its left-hand side are known, the rule can fire, adding its weight to the weight of the RHS value which it predicts. After all rules have had a chance to fire, the result is an  
20 array of weights for all possible values of the RHS attribute. The weights of all rules inferencing a particular RHS value are accumulated to produce the weight of that RHS value (step 1060b).

Resolving conflicts is necessary when two or more rules fire and inference a number of different RHS values (step 1060c). After exponentiating and normalizing the accumulated weights for the different RHS values to produce probabilities for each value, the system chooses one of these values at random. The system does not have to choose the answer probabilistically. If it does, it chooses the answer randomly, based on the probabilities generated by exponentiating the weights for the possible RHS values.

10 However, we could also simply choose the most likely answer.

#### - Summation of Rule Weights

When a rulebase is used to infer a RHS value, each rule in the rulebase is checked in order of decreasing rule J-measure. A rule can fire if it has not been marked dependent (see the next section on independence pruning) and all the attributes on its LHS are known. When a rule fires, its weight is added to the weight of the RHS value which it predicts. After all rules have had a chance to fire, the result is an array of weights for all possible values of the RHS attribute.

15

20

#### - Independence Pruning in Real Time

As explained in the section above on generation of dependence data, all rules which fire for a given LHS should be independent. However, the inventors realized that rulebases cannot be pruned ahead of time to remove rules without losing information.

The inventor's solution to this dilemma is to keep track of which rules are dependent on other rules, and only allow rules which are still independent to fire. This technique is described below.

Start by allocating and zeroing an array  $F$ , where  $f_i$  is zero if rule  $R_i$  is allowed to fire. Then for each rule  $R_i$  in order of decreasing J-measure,

1. If  $f_i$  is non-zero, the rule is not allowed to fire. Skip to the next rule.
2. If the rule can't fire, one of the attributes on the LHS of the rule is either unknown in the input data or does not have the right value to match the input data, skip to the next rule.?????
3. The rule can fire. Add its weight to the weight for the RHS value it predicts.
4. For each rule  $R_j$  in the list of rules dependent with  $R_i$ , set the corresponding  $f_j$  non-zero.

This technique is very fast, since it requires only array lookups and does no complex calculations. In fact, it is faster than using the same rulebase without dependency information, since if a rule is forbidden from firing the  
5 program does not spend time determining if the rule is allowed to fire. (With no dependency information, all rules are checked to see if they can fire.)

#### 4.3 Resolution of Conflicts Between Rules Which Fire

If all rules which fire on a given example inference  
10 the same RHS value, the result of the inference is clear. But if two or more rules fire and inference a number of different RHS values, one of two algorithms must be used to resolve the conflict. In either case, the weights of all rules inferencing a given RHS are accumulated to produce the  
15 weight of that RHS.

The simpler algorithm is termed "best-only." The RHS with the highest weight is always chosen. This is the most correct method from the standpoint of probability theory. However, the inventors realized that this tends to lead to  
20 monotonous music, since a given melody will always be harmonized in the exact same fashion.

This problem led to the development of a second algorithm.

The other option is to randomly select between the possible RHS values. The accumulated weights for the RHS values are exponentiated and normalized to produce probabilities for each value. The RHS value to be used is chosen randomly based on these probabilities. It is important to note that the algorithm only chooses between values which had rules fire, not all possible values for the RHS attribute. Otherwise, there would always be a non-zero probability of picking any RHS value, even if no rules fired for that value.

#### - 4.4 What If No Rules Fire?

If no rules for a given rulebase fire, there are two possibilities. If it is not the last part of a series of segmented rulebases, the next segmented rulebase will be given a chance to fire. If the rulebase is the last in the series, or is not part of a series of segmented rulebases, the RHS value is set to the most likely value of the RHS attribute based on the attribute's prior probability distribution. This is equivalent to classifying the RHS attribute with a zeroth-order Bayesian classifier.

This problem can be avoided by training a first-order Bayesian classifier and using it as the last segment in a series of rulebases for a given RHS attribute. (For example, basing the current chord function only on the  
5 current melody pitch and setting both the minimum probability for a rule and the minimum rule J-measure to zero.) Since the first-order classifier will always have exactly one rule which fires, more information will be used to pick the RHS value than if no rules fired at all.

10           - Conversion to MIDI

The output of harmonization is either saved in a MIDI file or played on a MIDI synthesizer, so conversion from figured bass back to MIDI is necessary (Fig. 10). MIDI data is produced for each timestep as follows. First, using  
15 the table of common functions and the voice position fields, the system determines for the chord which voices should play which pitches (step 1070a). Starting just below the melody note, which is known because it was used as the input to harmonization, the system then searches, once for each  
20 remaining voice, for an unplayed note matching that voice's pitch (step 1070b). Lastly, using MIDI code, the system indicates the notes found (step 1070c), the delays equal to

each note's duration (step 1070d), and corresponding note terminations (step 1070e).

Given the timestep below, for example, the system uses the table of common functions to determine that the "iii" chord has the pitches {E, G, B}. Based on the positions {I2, T1, A1, S0} with the soprano pitch agreeing with the melody field, the voices play pitches {B, G, G, E}, respectively. If the melody note were at octave 5, the MIDI conversion would turn on the notes {E5, G4, G3, B2}. In either case, the system would encode a delay and a termination corresponding to a duration of one-eighth note.

MEL	FUNC	IN	TP	AP	SP	DUR	ACC
E	iii	I2	T1	A1	S0	1	un

## 15 - Rulebases and Results

In the following discussion of the development of sets of rulebases, results from these sets of rule bases are analyzed and contrasted with each other. When rulebases are printed in a table, the columns have the following meanings.

RHS Attribute	LHS Attributes	Max Order	Number of Rules	Notes
5 The attribute present on the RHS of the rule base.	Attributes present on the LHS of the rule base. Rules <u>must</u> contain any attributes in bold, and <u>may</u> contain the other attributes.	The maximum number of terms allowed on the LHS of a rule.	The number of rules in the rule base.	Significant features of the rule base.

10 Unless otherwise noted, all rules should be correct at least 50% of the times they fire and should have a J-measure of at least 0.001. The rules discussed below were trained from an example set of 15 Bach harmonized chorales, which produced 818 examples by beat-based conversion and 834

15 examples by chord-based conversion.

The first attempt at generating harmony rules used no rule base segmentation, filtering, or pruning. The resulting rule base, called Simple1, was trained from examples using beat-based conversion.



RHS Attribute	LHS Attributes	Max Order	Number of Rules	Notes
Function0	Function1, Melody1, Melody0	3	105	

This initial rule base had a number of limitations.

- 5 Of its 105 rules, 33 do not use the current melody note or the previous function, which lead to unresolved dissonances in the harmony. For example, if the current melody note was F-sharp and the previous function was a V7 chord, the following rule led the rule base to play a C Major chord.

10 12. IF Function1 V7 THEN Function0 I : 0.566 0.343 0.030

The C Major chord sounds very dissonant against the F-sharp in the melody.

- To correct the problems in the first rule base Simple1, all rules which did not use both the current  
 15 function and previous melody note were filtered out, producing a new rule base Simple2.

RHS Attribute	LHS Attributes	Max Order	Number of Rules	Notes
Function0	Function1, Melody1, Melody0	3	72	

However, this smaller rule base frequently failed to fire on its input. This led to the following harmonization of the first phrase of "Hark, the Herald Angels Sing:"

	Melody	Chord	Rules Fired
5	G4	I	0
	C5	I	0
	C5	I	0
	B4	I	0
	C5	I	0
10	E5	I	2
	E5	I	2
	D5	V	2

Too much information had been lost, so no rules were fired for over half the timesteps, producing an extremely dull harmony. The smaller rule base sounded worse, because dissonances were created when no rules fired and the C-Major chord picked by the Bayes classifier of order zero was played against notes such as F and B.

The solution to the problems that the inventors recognized with respect to the first two rule bases lay in segmenting the learned harmony rules into three rule bases, together called Major4 and listed in the table below. These rule bases were the first to be used in real time to accompany a musician. The musician played only the melody

note and the program responded with the other three voices a fraction of a second later.

The first rule base contained the best rules, used in the Simple2 set. If no rules from that set fired, the  
5 second rule base tried to fire rules which used at least the current melody note. As mentioned above with respect to segmentation, this method allowed the better rules a chance to fire without being overwhelmed by rules using less significant information, while preserving all of the  
10 information contained in the full rule base.

If no rules fired in any of the three initial rule bases, which happened about 25% of the time, a first-order Bayesian classifier would determine the current function based on the current melody note. This ensured that the  
15 chord played would be at least consonant with the melody note.

These rules worked well enough that additional rule bases were generated to determine the positions of the bass, alto, and tenor voices so that the harmonized melody could  
20 be converted back into MIDI data and played, as described above. Bayesian classifiers were not needed in addition to these rule bases, because (1) the generated rules spanned a much larger portion of the input space, i.e., only rarely

did no rule fire, and (2) because an error in a single voice position is much less noticeable than a bad chord function.

5

10

RHS Attribute	LHS Attributes	Max Order	Number of Rules	Notes
Function0	Function1, Melody1, Melody0	3	172	First of four rule bases used to predict harmony.
Function0	Melody1, Melody0	3	34	
Function0	Function1, Melody1	3	37	
Function0	Melody0	1	8	First-order Bayesian classifier.
Inversion0	Function1, Inversion1, Function0	3	145	
Alto0	Function1, Alto1, Function0, Inversion0	3	472	
Tenor0	Tenor1, Function0, Inversion0, Alto0	3	341	

Some of the significant rules in these rule bases included the following.

The first rule is from the first Function0 rule base.

5     1. IF Melody0 E                    THEN Function0 I 0.83 0.89 0.0601  
      AND Function1 V

This transition, from G Major to C Major, is the strongest cadence or ending in classical harmony.

10    3. IF Melody0 F                    THEN Function0 IV 0.98 3.12 0.0499  
      AND Function1 V

This is another common transition, from G Major to F Major.

The following rule is from the Inversion0 rule base.

15    1. IF Function1 V                    THEN Inversion0 I1 0.98 1.59 0.0255  
      AND Function0 IV

Combined with rule 3 above, this rule places the function V to function IV transition in first inversion.

3. IF Function1 V                    THEN Inversion0 I0 0.86 0.20 0.0179  
   AND Function0 I

20        Combined with rule 1 above, this places the function V to function I cadence in root position, which is the strongest position for an ending chord.

26.       IF Function0 vii07 THEN Inversion0 I1 0.53 0.17 0.0098

25        This rule places diminished 7th chords in first inversion, where they are placed in classical harmony. This

rule has a lower J-measure than the other rules because diminished 7th chords do not appear very often, which creates a low value for  $p(y)$ .

With the "best-only" method turned off as described  
 5 above, the system was able to produce different harmonies for a given melody by randomly choosing among possible RHS values. For example, the melody C-A-B-G-D-C could be harmonized as follows.

	C Major	I0 A0 T2 C5 : I	{ C3 G3 C4 C5 }
10	D Major	I0 A2 T0 A5 : V/V	{ D3 D4 A4 A5 }
	G Major	I0 A1 T2 B5 : V	{ G3 D4 B4 B5 }
	G Major	I1 A2 T0 G5 : V	{ B3 G4 D5 G5 }
	G Major	I0 A1 T2 D5 : V	{ G3 D4 B4 D5 }
	C Major	I0 A0 T2 E5 : I	{ C4 G4 C5 E5 }

15 Alternatively, the melody could be harmonized as shown below.

	C Major	I0 A0 T2 C5 : I	{ C3 G3 C4 C5 }
	D Major	I0 A2 T0 A5 : V/V	{ D3 D4 A4 A5 }
	G V7	I0 A3 T3 B5 : V7	{ G3 F4 F5 B5 }
20	C Major	I0 A0 T1 G5 : I	{ C4 E4 C5 G5 }

B dim7            I1 A3 T1 D5 : vii07 { D3 D4 G#4 D5 }  
 A Minor           I0 A1 T0 C5 : vi        { A2 A3 C4 C5 }

The two harmonizations are quite different: in the  
 six-note melody above, there are three places where the  
 5 program has a choice between two functions for a given  
 chord.

Another piece harmonized by these rule bases, the  
 first phrase of "Hark! the Herald Angels Sing" shown in Fig.  
 11, has a generally high-quality sound - there are no  
 10 unresolved dissonances. However, the voice-leading in the  
 piece is poor in places. The third chord, a C Major chord,  
 has notes {C, C, C, G}. The third note of the chord, E, is  
 absent, leading to a hollow sound. This problem was  
 addressed in the next set of rule bases, called Major4a and  
 15 discussed below.

In an attempt to correct the voice leading problems  
 of the Major4 rule base, a rule base which determined the  
 soprano voice position was added to the set of rule bases.  
 Since the current function and melody pitch uniquely  
 20 determine the soprano voice position, the generated rule  
 base covered the entire input domain and was always correct.

The soprano voice position was added to the possible LHS attributes for the rule bases for the other voice positions. This permitted rules for the tenor which would allow the tenor to fill in a missing chord pitch. The tenor rules were no longer forced to include the chord position. The addition of the soprano voice allows rules such as the following.

2.	IF	Soprano0	S1	THEN Tenor0 T2 : 0.888 1.024	0.132
10	AND	Alto0	A0		
	AND	Inversion0	I0		
6.	IF	Soprano0	S0	THEN Tenor0 T1 : 0.901 1.239	0.079
15	AND	Alto0	A2		
	AND	Inversion0	I0		
13.	IF	Soprano0	S2	THEN Tenor0 T3 : 0.634 1.326	0.070
20	AND	Alto0	A1		
	AND	Inversion0	I0		
	AND	Tenor1	T0		

These rules show the tenor rule base filling in chord pitches which are not present in the other rule bases. The very high accuracy of the first two rules (88.8% and 90.1%) indicates that it is important to fill out a chord's pitches.

The number of rules is then reduced by subsumption pruning of the rulebases, resulting in the Major4a set shown in the table below. This pruning removed from 5% to 30% of



the rules from any given rule base without affecting its classification accuracy or input domain.

RHS Attribute	LHS Attributes	Max Order	Number of Rules	Notes
Function0	Function1, Melody1, Melody0	3	124	
Function0	Melody1, Melody0	3	32	
Function0	Function1, Melody1	3	26	
Function0	Melody0	1	8	First-order Bayesian classifier.
Soprano	Melody0, Function0	2	60	Direct equivalence between LHS and RHS.
Inversion0	Function1, Inversion1, Function0, Soprano0	4	133	
Alto0	Function1, Alto1, Function0, Inversion0, Soprano0	4	309	
Tenor0	Tenor1, Function0, Inversion0, Alto0, Soprano0	4	434	

Fig. 12 shows the harmony for "Hark! The Herald Angels Sing" generated by the new rules. The third chord, which used the voice arrangement {C,C,C,G} under Major4, uses {C,G,E,G} under Major4a and contains all three pitches present in the C Major chord. Furthermore, the new rules

doubled the G note, as is proper for a chord present in second inversion.

Despite the progress in voice-leading, the Major4a rules still had limitations. For instance, the rules  
5 referred back in time only to the previous chord, and did not use information about the accent on the current chord. This meant that the rule base could not predict when a piece of music was ending, and thus often fumbled the final cadence. An example of this problem is shown in Fig. 13 in  
10 the harmony produced for "Happy Birthday." The harmony ends on a "vi" or "A Minor" chord, which, being a minor chord, lends a sad feel to the end of the piece. This is not an appropriate way to end a piece written in a major key.

The Major7a set of rule bases, listed below, was  
15 allowed to use more information about the accents of current and previous chords. "FunctionLA" stands for the function of the last chord which started on an accented beat. "FunctionLB" and "InversionLB" represent the function and inversion, respectively, of the last chord which started at  
20 the beginning of any beat. "Accent0" means the accent on the current chord. "Function1" still stands for the function of the immediately preceding chord.

With the Bach chorales used as input, either FunctionAB or FunctionLB did not match a common function 14% of the time. The method could not find a match for Function1 in 25% of the examples. Since unmatched functions  
5 typically indicate that an ornament is present, this result confirms that ornaments occur more frequently in the middle of beats.

Rules were required to be correct at least 30% of the time they fired, which was lower than the 50% required  
10 by previous sets of rule bases. However, the largest prior probability for Function0 was 24%, so a rule which was correct 30% of the time still provided useful information. All rule bases were also subsumption pruned.

5

10

RHS Attribute	LHS Attributes	Max Order	Number of Rules	Notes
Function0	FunctionLA, FunctionLB, Function1, Melody1, Accent0, Melody0	5	175	First of four segments of Function0 rules.
Function0	(FunctionLA and/or FunctionLB), Melody1, Accent0, Melody0	5	282	
Function0	Melody1, Accent0, Melody0	5	83	
Function0	FunctionLA, FunctionLB, Function1, Melody1, Accent0	5	361	
Soprano0	Function0, Melody0	2	60	Direct equivalence between LHS and RHS.
Inversion0	FunctionLB, Function1, Inversion1, Function0, Soprano0	5	332	First of two segments of Inversion0 rules.
Inversion0	FunctionLB, Function1, Inversion1, Soprano0	5	287	
Alto0	Function1, Alto1, Function0, Inversion0, Soprano0	5	820	
Tenor0	Tenor1, Function0, Inversion0, Alto0, Soprano0	5	815	

Rules had more possible LHS attributes and higher order rules were permitted, so enough rules were generated that at least one rule would fire for each desired RHS attribute in almost all cases. Therefore, a Bayesian classifier was not needed as a safety net for determining the chord function.

The script for determining the major7 follows.  
Lines which start with ; are comments.

```
10 ;      Read examples from the example list
;
load exlist major7 from major7.el

;
15 ;      Set defaults

;      At most 5 clauses on "IF" side of a rule
default rule order 5

20 ;      Unless otherwise specified, learn using the "major7"
;      example list we just read in
default exlist major7

;      Learn up to 2048 rules at a time
25 default maxrules 2048

;      Rules must be right at least 30% of the time
default mincorrect 0.3

30 ;      Rules must have a J-measure >= 0.001
default minpriority 0.001

;=====
=====
35 ;      Extract and save attributes
;
copy attrbase attr7 from major7
```

```

save attr7 to attr7.att

;=====
=====
5 ;      Learn rules for Harmony0
;
learn harm7_2 {
; These attributes CAN appear on the left-hand side
lhs Melody0
10 lhs Melody1
lhs Function1
lhs FunctionLB
lhs FunctionLA
lhs Accent0
15 ; This is what we want to predict
rhs Function0
}

;
20 ;      Now we want to segment the harmony rules into 3
different
;      sets, based on what attributes they contain.
;

25 ;
;      Ruleset #3 - doesn't use current melody
;

30 ;      Copy the full set of rules
copy rulebase harm7_3 from harm7_2
;      Remove any rules which use Melody0
filter harm7_3 never Melody0
;      Do subsumption pruning
35 prune harm7_3
;      Save the rulebase
save harm7_3 to harm7_3.rul
;      And free up its memory
free harm7_3

40 ;      Rulesets #1,2 - use current melody and last
functions
;      Now remove all the rules which ended up in harm7_3
filter harm7_2 always Melody0

```

```

;      And resize the rulebase (this frees up the memory
which
;      was used by the rules we just filtered out)
resize harm7_2
5
;
;      Ruleset #1 - use either Function1, FunctionLB, or
FunctionLA
;
10
;      In order to handle the "OR" in the statement above,
we need
;      to make three sub-rulebases - each contains rules
which use
15
;      one of the Function attributes.
copy rulebase h71a from harm7_2
filter h71a always Function1
prune h71a
resize h71a
20
copy rulebase h71b from harm7_2
filter h71b always FunctionLB
prune h71b
resize h71b
copy rulebase h71c from harm7_2
25
filter h71c always FunctionLA
prune h71c
resize h71c

;      Now we combine the three sub-rulebases into one big
30
rulebase.
combine h71a and h71b into h71d
free h71a
free h71b
combine h71c and h71d into harm7_1
35
free h71c
free h71d

;      Once they're combined, we can subsumption-prune the
result.
40
prune harm7_1
save harm7_1 to harm7_1.rul
free harm7_1

;      Ruleset #2 - doesn't use any functions
45
filter harm7_2 never Function1

```

```

filter harm7_2 never FunctionLB
filter harm7_2 never FunctionLA
prune harm7_2
save harm7_2 to harm7_2.rul
5 free harm7_2

;=====
=====
;      Learn rules for Soprano0 (should do perfectly -
10 there's
;      a 1:1 mapping between Function0+Melody0 and
Soprano0)
;
learn sopr7_1 {
15 ruleorder 2
mincorrect 0.2
minpriority 0.000001
lhs Melody0
lhs Function0
20 rhs Soprano0
}
filter sopr7_1 always Melody0
filter sopr7_1 always Function0
save sopr7_1 to sopr7_1.rul
25 free sopr7_1

;=====
=====
;      Learn rules for Inversion0
30 ;
learn invr7_2 {
lhs Function0
lhs Soprano0
lhs Inversion1
35 lhs Function1
lhs InversionLB
lhs FunctionLB
lhs Accent0
rhs Inversion0
40 }

;      Ruleset #1 - use current function
copy rulebase invr7_1 from invr7_2
filter invr7_1 always Function0
45 prune invr7_1

```



```

save invr7_1 to invr7_1.rul
free invr7_1

;      Ruleset #2 - don't use current function
5 filter invr7_2 never Function0
  prune invr7_2
  save invr7_2 to invr7_2.rul
  free invr7_2

10 ;=====
    ;      Learn rules for Alto0
    ;
    learn alto7_1 {
15   lhs Function0
      lhs Soprano0
      lhs Inversion0
      lhs Function1
      lhs Alto1
20   lhs Accent0
      rhs Alto0
    }
    prune alto7_1
    save alto7_1 to alto7_1.rul
25   free alto7_1

    ;=====
    ;      Learn rules for Tenor0
30   ;
    learn tenr7_1 {
      lhs Function0
      lhs Soprano0
      lhs Alto0
35   lhs Inversion0
      lhs Function1
      lhs Tenor1
      rhs Tenor0
    }
40   prune tenr7_1
    save tenr7_1 to tenr7_1.rul
    free tenr7_1

;      We're done with this section of the learning, so
45 exit this script.

```

end

This Major7a set of rule bases produces the harmony for "Happy Birthday" shown in Fig. 14. Unlike Major4a, Major7a directs that the piece should end on a "I" or C Major chord, which is a more solid ending for a piece in a major key.

The Major7b set of rule bases, shown in the table below, is identical to the Major7a set except for the addition of dependency data for real time independence pruning. The number of dependent rule pairs for each rule base is shown in the table.

15

RHS Attribute	LHS Attributes	Number of Rules	Number of Dependent Rules	Average Pairs Per Rule
Function0	FunctionLA, FunctionLB, Function1, Melody1, Accent0, Melody0	175	175	1.0
Function0	(FunctionLA and/or FunctionLB), Melody1, Accent0, Melody0	282	249	0.9
Function0	Melody1, Accent0, Melody0	83	32	0.4
Function0	FunctionLA, FunctionLB, Function1, Melody1, Accent0	361	553	1.5

Soprano0	Function0, Melody0	60	0	0.0
Inversion0	FunctionLB, Function1, Inversion1, Function0, Soprano0	332	694	2.1
Inversion0	FunctionLB, Function1, Inversion1, Soprano0	287	597	2.1
Alto0	Function1, Alto1, Function0, Inversion0, Soprano0	820	1992	2.4
Tenor0	Tenor1, Function0, Inversion0, Alto0, Soprano0	815	2868	3.5

5                   The position-oriented rule bases, which have more  
 LHS attributes which take only a few values, end up with  
 higher numbers of dependent rule pairs. This leads to  
 situations such as the following. If the Tenor0 rule base  
 10 contains the rule

IF Soprano0 = S2           THEN   Tenor0 = T1

then the Tenor0 rule base is likely to contain one or more  
 of the following rules

15   IF   Soprano0 = S2           THEN   Tenor0 = T1  
      AND   Tenor1 = T0

```
IF Soprano0 = S2      THEN Tenor0 = T1
AND Tenor1 = T1
```

```
IF Soprano0 = S2      THEN Tenor0 = T1
AND Tenor1 = T2
```

```
5 IF Soprano0 = S2      THEN Tenor0 = T1
AND Tenor1 = T3
```

because a subset of examples with a specified value for Tenor1 has a sufficiently large number of samples to force up the J-measure for rules with that Tenor1 value on the

10 LHS.

The addition of real time independence pruning speeds up harmonization because fewer rules in each rule base need to be checked to see if they can fire. However, the harmony generated by the newer rule bases does not

15 differ significantly from that of the Major7a rule bases.

The following script is used:

```
; MAJOR7B.INP - generates dependence info for major7 rules
; We did this as a separate script so I could look at the
intermediate
20 ; steps - there's no reason we couldn't do it in the same
script that
; we learned the rules in.
;

25 ;
; Load our examples and attributes.
;
load exlist m7 from major7.el
copy attrbase a7 from m7
30 default attrbase a7

;
; Now we load in each rulebase and generate its dependency
information.
```

```
;  
; Load the rulebase  
load rulebase r from r\harm7_1.rul  
5 ; Generate its dependency information  
gendep r with m7 0.5  
; And save it  
save r to harm7_1b.rul  
; Then free up the memory it was using.  
10 free r  
  
load rulebase r from r\harm7_2.rul  
gendep r with m7 0.5  
save r to harm7_2b.rul  
15 free r  
  
load rulebase r from r\harm7_3.rul  
gendep r with m7 0.5  
save r to harm7_3b.rul  
20 free r  
  
load rulebase r from r\harm7_4.rul  
gendep r with m7 0.5  
save r to harm7_4b.rul  
25 free r  
  
load rulebase r from r\invr7_1.rul  
gendep r with m7 0.5  
save r to invr7_1b.rul  
30 free r  
  
load rulebase r from r\invr7_2.rul  
gendep r with m7 0.5  
save r to invr7_2b.rul  
35 free r  
  
load rulebase r from r\alto7_1.rul  
gendep r with m7 0.5  
save r to alto7_1b.rul  
40 free r  
  
load rulebase r from r\tenr7_1.rul  
gendep r with m7 0.5  
save r to tenr7_1b.rul  
45 free r
```

end

- File Format

The following describes a specification of a  
5 preferred data file format for transmitting information  
about examples and rules among different applications. The  
format allows for expansion of the specification while still  
permitting older applications to read newer and expanded  
data files. Any application which implements the required  
10 portions of the specification is able to read and use those  
portions of any data file written using any version of the  
specification.

The preferred file extension is ".IPR," which stands  
for Itrule Portable Rule ("IPR") file.

15 An IPR file includes ASCII text. The first ten  
characters of an IPR file should be "#IPRSTART#" which  
permits application readers to detect and reject easily  
files which are not IPR files. The file terminates with the  
text string "#IPREND#" followed by an End-of-File ("EOF")  
20 character, which is 0x1A in hexadecimal notation. Lines can  
terminate with any combination of carriage-return (0x0D) and  
line feed (0x0A) characters. The line length limit is 16384  
characters.

IPR files can consist of any number of sections -  
for example, an IPR file with zero sections is meaningless,  
but permissible. All identifiers and variable names are  
case-insensitive. Identifiers and variable names should  
5 begin with a letter, i.e., A to Z, and should not contain  
space characters or any of the following characters:

{ } = , " < | >

Identifiers and variable names can be up to 31 characters  
long. Values can be up to 255 characters long.

10 Each section of the data file has the following  
form.

```
SECTIONTYPE {  
    ...data for section...  
}
```

15 The "SECTIONTYPE" identifier is not required to be  
on the same line as the open brace and no space is required  
between the identifier and the open brace.

Under the specification, a program which does not  
recognize a section type should ignore it. Sections can be  
20 nested, e.g., a "RULE" section can be nested inside a  
"RULEBASE" section. A nested section is referred to as a  
"subsection." Within a section, all variables should come  
first, followed by any subsections.

Comment notation is similar to that of the programming language C++. Single-line comments begin with two slashes "//" and extend to the end of the line, as shown below.

5           // This is a comment

Comments with multiple lines, such as the sample comment below, begin with slash-star "/\*" and end with star-slash "\*/".

10           /\* This is a comment  
              which can extend  
              over multiple lines \*/

Any text denoted a comment should be ignored by programs.

Variable assignments have the following form.

variable = value

15   A value containing spaces or tabs should be enclosed in double-quotes, as shown below.

variable = "multi word value"



Spaces between the variable, equals sign "=", and the value are optional. A program reading an assignment should be able to understand the assignment with or without the spaces.

5           Some variables are optional and can be absent from an IPR file - a program is not required to be able to read or write these variables. A program encountering a variable unknown to it should be able to pass over that variable without disruption.

10           A required variable is indicated by a denotation "(required)" which follows the variable's definition. All reader applications and writer applications should process these variables.

          Variables have assigned types which follow their  
15 definitions: "string" denotes an ASCII string, "integer" indicates a 4-byte signed integer, and "float" signifies a floating point number.

          Some section types are pre-defined. A "RULEBASE" section is used to store lists of rules and consists of a  
20 series of variables followed by a series of rule sections, as shown below.

```
RULEBASE {
```

```

// variables:
NAME = string
COUNT = integer
ATTRIBUTESFROM = string
5  DEPENDENCYCOUNT = integer (*Enumerates the size of
    dependency table*)
    ...

// list of rules:
10  RULE {
    ...rule data...
}
    RULE {
    ...rule data...
}
15  ...

// realtime dependency table
DEPENDENCYTABLE {
    ...dependency data...
}
20  }

```

In the "RULEBASE" section, the variable "NAME (string, required)" has the rule base's name, which can be up to 256 characters in length. A variable "DEPENDENCYCOUNT (integer, optional)" indicates the number of elements in the

25 real-time dependency pruning table and should be present if the "DEPENDENCYTABLE" subsection is present. The number of rules in the rule base is stored by the variable "COUNT (integer, required)."

An attribute data base, in terms of which the rule

30 base is defined, should precede the rule base in the IPR

file and is indicated by variable "ATTRIBUTESFROM (string, required)."

Two sections contained in a "RULEBASE" section are "DEPENDENCYTABLE (optional)" and "RULE (required)." The  
 5 "DEPENDENCYTABLE" section contains real-time dependency information for the rule base and is stored as a series of integers separated by spaces. The "RULE" section stores a single rule and is contained in a "RULEBASE" section.

A "RULE" section has the structure shown below.

```

10  RULE  {
        PRIORITY = float
        WEIGHT = float
        J-MEASURE = float
        LITTLE-J = float
15      P (FIRE) = float
        P (CORRECT) = float
        DEPENDOFFS = integer
        ...

        IF {
20          // permissible if clauses:
            {attr = value}
            {attr <> value}
            {attr > value}
            {attr < value}
25          {attr >= value}
            {attr <= value}
        }

        IFOR {}
        IFAND {}
30      THEN {
            {attr = value | weight}
  
```

```

        {attr = value | weight}
        ...
    }
    THENDISTR {
5      {attr | weight1 weight2 weight3...
    }
}

```

An example of an "IF" clause is shown below.

```

10 // if {a1=v1 and a2=v2 and (a3=v3 or a4=v4))
    IFAND {
        {a1 = v1}
        {a2 = v2}
        IFOR {
15      {a3 = v3}
        {a4 = v4}
        }
    }
}

```

In a "RULE" section, the variable "PRIORITY (float, optional)" indicates the rule's priority, in arbitrary units. Rule weight is signified by the variable "WEIGHT (float, optional)" which stores the logarithm of the rule's transition probability. The variables "J-MEASURE (float, required)" and "LITTLE-J (float, optional)" contain the rule's J-measure and j-measure, respectively. The probability, based on the training examples, that the rule will be able to fire is indicated in the variable "P(FIRE) (float, optional)." Related variable "P(CORRECT) (float,

optional)" represents the probability, again based on the training examples, that the rule, if able to fire, will be correct. If a dependency table is used, the variable "DEPENDOFFS (integer, optional)" shows the offset position, in the realtime dependency table, of the rule's dependency information.

Subsection "IF (required)" has a standard left-hand side with "attribute = value" pairs and should not have nested boolean expressions. The attribute and value should conform to the specifications for variables.

Subsection "IFAND (optional)" is equivalent to subsection "IF." Subsection "IFOR (optional)" returns a boolean value of "TRUE" if one or more of its "attribute = value" pairs matches the input data. Subsections "IFAND" and "IFOR" can be nested within each other.

The subsection "THEN (required)" has a standard right-hand side with "attribute = value|weight" sets. The "weight" field, which is optional, represents the fraction of the total rule weight, indicated by the WEIGHT variable discussed above, which should be added to the logarithmic probability for the RHS value. The "weight" fields are not required to add up to 1.0. An omitted "weight" field is treated as a "weight" field of 1.0. As mentioned above, the

attribute and value should conform to the specifications for variables. Distribution rules can be represented by a "THEN" subsection which has one triplet for each possible RHS value or by a "THENDISTR (optional)" subsection which  
5 specifies an attribute and lists the weights for each value of that attribute in order.

As mentioned above, each rule base is defined in terms of an attribute base. An "ATTRBASE" section, which has the form shown below, stores an attribute base, i.e., a  
10 series of attributes, just as a "RULEBASE" stores a series of rules.

```
ATTRBASE {  
    // variables:  
    NAME = string  
15    COUNT = integer  
    ...  
  
    // list of attributes:  
    ATTRIBUTE {  
        ...attribute data...  
20    }  
    ATTRIBUTE {  
        ...attribute data...  
    }  
    ...  
25 }
```

The "NAME (string, required)" variable in the attribute base stores the attribute base's name, which can

be up to 256 characters in length. The number of attributes in the attribute base is represented by COUNT (integer, required).

The "ATTRIBUTE (required)" subsection has the structure shown below.

```

ATTRIBUTE {
    // variables:
    NAME = string
    COUNT = integer
10    UNKNOWN = float
    ...

    // values
    VALUES {
15        {value | probability}
        {value | probability}
        {value | probability}
        ...
    }
}

```

The variables of the "ATTRIBUTE" subsection include the "NAME (string, required)" variable which stores an attribute name of up to 256 characters in length and the "COUNT (integer, required)" variable which represents the number of values for the attribute. Another variable

25 "UNKNOWN (float, optional)" indicates the fraction of the attribute's values that are unknown. A list of values and a

probability for each value is stored by the "VALUES (required)" variable.

The "RBASELIST" subsection is a section containing a list of rule bases and has the structure shown below.

```

5  RBASELIST {
    // variables:
    NAME = string
    COUNT = integer
    // filename for attrbase
10  ATTRBASE = string

    // rulebases in order
    RBLIST {
        {name | flag1 flag2...}
        {name | flag1 flag2...}
15  ...
    }
}

```

Like other sections, the "RBASELIST" section has a "NAME (string, required)" variable and a "COUNT (integer, required)" variable. The "COUNT" variable represents the number of rule bases in the list. The common attribute base for the rule base list is indicated by the variable "ATTRBASE (string, required)."

The "RBASELIST" section also has a subsection "RBLIST (required)" which stores a list of data file names for rule bases and flags for each rulebase.



- Software Interface

The following describes a specification of a preferred Windows operating system interface between a shared rule-based inferencing software engine (the "server") and software applications which use the engine to learn and evaluate rule bases for real-time control (the "clients"). All applications, client-based and server-based, register three custom message numbers for communication, and use them to communicate commands and results between each other. The message numbers used are returned by the following actions.

```
AdmireControlMsg = RegisterWindowMessage ("ADMIRE/WIN Control");  
AdmirePacketMsg = RegisterWindowMessage ("ADMIRE/WIN Packet");  
AdmireFreePtrMsg = RegisterWindowMessage ("ADMIRE/WIN FreePtr");
```

Messages are sent between client and server using Windows procedure "PostMessage ()". This allows the rule base engine and clients to function asynchronously. Applications should not send messages using Windows procedure "SendMessage ()," which, unlike "PostMessage ()," does not give up control in the Windows cooperative multitasking environment.

When a message is sent, Windows structure "wParam" always contains the handle of the sending window, so the

receiver can easily determine where to send a reply. The value of Windows structure "lParam" depends on the type of message being sent.

A Control Message is used to initiate or terminate a communication or to send other application-level control messages. Accordingly, "lParam" is set as shown in the following table.

HIWORD	LOWORD	Meaning
1-HELLO	0	Client is broadcasting a request to all servers to initiate communication.
	1	Free server is responding to a client.
	2	Busy server is responding to a client.
	3	Client wants this server - server become busy.
	4	Client does not want this server - server becomes free.
2-BYE	0	Client or server is requesting connection be terminated.

A Packet Message is used to send packets between the client and server once communication has been established. In this case, "lParam" is a pointer to the packet data, which lies in global shared memory. Once a packet has been passed to another program via this interface, the sending program should not attempt to access the packet data. When the receiving program is done with the packet, it should

send a Free Pointer Message back to the sender so that the sender can free the associated memory.

The Free Pointer Message is sent to the original sender of a packet, signifying that the original receiver is done with the packet and that the memory associated with the packet can be freed. "lparam" should point to the memory to be freed.

All communications packets consist of a series of data structures called "chunks." Each chunk has the form shown in the table below.

Addresses	Type	Contents
0000-0003	ASCII chars	Chunk type, not a null-terminated string.
0004-0007	32-bit integer	Length of chunk including the header.
0008-0009	16-bit integer	Offset of start of chunk body from start of chunk.
000A-nnnn	Various	Chunk body.

All packets should begin with a header chunk "\*HDR" and end with an end chunk "\*END." Encoding the offset of the chunk body as noted in the table above allows more fields to be added to the chunk header.

Each packet should handle only one subject, e.g., loading a series of files or learning a rule base. It is

preferable to send multiple small packets instead of one large complex packet, so that the sending of information does not entail large delays which can disrupt the multitasking environment.

- 5 All applications should be able to process all chunk types beginning with an asterisk "\*." Processing other chunk types is optional. If an application does not understand one or more chunks in a packet, it should send an "\*UNK" chunk back to the sender of the packet as part of any  
10 reply to the packet.

The "\*HDR" header chunk is the first chunk in any packet and contains subfields in the chunk body as indicated in the following table.

Addresses	Type	Contents
15 0000-0003	32-bit integer	Packet ID number. ID numbers should be unique within a particular session.
0004-0007	32-bit integer	ID of the packet responding to, or 0 if this packet is not responding to a previous packet.
0008-0009	16-bit integer	Number of chunks in this packet, including the "*HDR and *END chunks."
000A-000B	2 8-bit integers	Version of the specification supported, in the form A.B.

The "\*UNK" chunk lists all the chunk types in a previous message that were not understood by the receiver. The chunk body thus consists of 4n bytes, where n chunk types were not understood, since each chunk type is a 4-byte string. This allows the sender to compensate for an older receiver which does not understand newer chunk types.

An "\*ERR" chunk indicates that a chunk was malformed, was missing a required field, or was otherwise unintelligible. The body of the "\*ERR" chunk contains the fields listed in the following table.

Addresses	Type	Contents
0000-0003	32-bit integer	Address of the bad chunk in the referenced packet.
0004-0007	32-bit integer	Offset of the error in the chunk.
0008-0009	16-bit integer	Type of error according to the following list.

Error Type	Meaning
0000	Unexpected end of packet.
0001	Missing required field.
0002	Invalid value for field.
7FFF	Last globally-defined error type.
8000-FFFF	Chunk-specific errors - possible errors are listed with each chunk type.

The "\*END" chunk should be the last chunk in a packet and has no body.

A "\*WHN" chunk states the conditions, listed in the following table, under which the receiver should send back a response or series of responses to the sender.

Addresses	Type	Contents
0000	8-bit integer	ONERROR-When errors should be sent.
0001	8-bit integer	WAITONERR-What should be done when an error is sent.
0002	8-bit integer	ONBUSY-What should be done if receiver is busy.

10 The integer "ONERROR" determines when the receiver should send errors generated by parsing the packet. It has one of the values listed below.

Value	Meaning
0 (default)	Send errors as soon as they are detected - one error per response packet.
1	Send errors as soon as the entire packet has been parsed - all errors in one response.
2	Send errors after the command completes - prepend the errors to the response to the command.

The "WAITONERR" integer, which has one of the values listed below, determines whether the receiver should wait for a response to any error messages before proceeding.

	Value	Meaning
5	0 (default)	Wait for a response from the sender before continuing processing of the packet.
	1	Continue processing the packet after sending any errors.

The "ONBUSY" integer, using one of the values below, indicates what the receiver should do if it is unable to process the commands in the packet immediately.

10	Value	Meaning
	0 (default)	Queue the command for processing.
	1	Queue the command for processing. Inform the sender that the command has been queued.
	2	Queue the command for processing. Inform the sender when the command has been queued, and again when the receiver starts processing the command.
	3	Do not queue the command. Inform the sender the command could not be processed.

Some commands, e.g., "WHER" and "ABRT," which are described below, are not queued but instead are processed ahead of other queued commands.

A "\*CMD" chunk contains the main command to be processed in the packet and is organized as shown in the table below.

Addresses	Type	Contents
00000-0003	ASCII	Command type, not a null-terminated string.
0004-nnn	Various	Command-specific fields.

A "COMM" or comment chunk contains null-terminated ASCII text and can be ignored safely by all applications.

A "PRED" chunk lists dependencies for a packet, i.e., lists the packet IDs whose commands should be completed before the current packet can be processed. If a "PRED" chunk is not present, the system assumes there were no predecessors to the current packet. The chunk body thus consists of n 32-bit packet ID's, i.e., 4n total bytes. The "PRED" chunk is necessary because packets can be queued asynchronously. For example, a packet which requests that rules be learned from examples should list as a predecessor the packet which loads the examples. The "PRED" chunk also allows for parallel or distributed processing of commands.



A "DEFS" chunk contains default values for the rule engine and is organized as shown in the table below. If a field has a value of -1 or contains an empty ASCIIZ, i.e., null-terminated, string, the present value is retained. If this chunk is sent to a server, the server's default values are changed to those specified in this chunk for all subsequent commands. Commands queued ahead of this chunk are not affected.

Addresses	Type	Contents
0000-0001	16-bit integer	Maximum rule order to be learned.
0002-0005	32-bit integer	Maximum number of rules to be learned.
0006-0009	32-bit float	Small sample k for statistics.
000A-000D	32-bit integer	Minimum number of rules which should agree with each rule to be learned.
000E-0011	32-bit float	Minimum probability that learned rule is correct.
0012-0015	32-bit float	Minimum rule priority to keep when learning rules.
0016-0035	ASCIIZ string	Attribute base.
0036-0055	ASCIIZ string	Rule base.
0056-0075	ASCIIZ string	Rule base list.
0076-0095	ASCIIZ string	Example list.

The "DIRS" chunk appears as shown below and lists all objects of the specified type that are present in server memory.

5	Addresses	Type	Contents
	0000	8-bit integer	Type of objects listed, or 0 for all objects.
	0001-0002	16-bit integer	Number of objects listed.
	0003-0004	16-bit integer	Size of each list entry in bytes.
	0005-????	Various	List entries.

List entries have the format shown below.

10	Offset	Type	Contents
	0000-001F	ASCIIZ string	Name of object.
	0020	8-bit integer	Type of object.
	0021-0024	32-bit integer	Number of things, <u>e.g.</u> , examples, rules, in object.
	0025-0028	32-bit integer	Size of object in bytes.

15           A packet can contain any number of command chunks, including none. All commands in a packet should be related to each other. Command chunks can contain command-specific data starting at offset 0004 within the command chunk data.

A "WHER" command chunk is sent from a client to request the status of a server. This command should always be processed asynchronously, regardless of how many packets are queued when the command is received. The server sends  
 5 back a "HERE" chunk in response. The "WHER" chunk is organized as shown in the following table.

Addresses	Type	Contents
0004-0007	32-bit integer	Type of status information requested, listed in table below.

A "HERE" chunk contains the fields listed in the  
 10 following table.

Addresses	Type	Contents
0004-0007	32-bit integer	Type of status information requested; list of types noted under "WHER" command.
0008-nnn	Various	Specific status information.

The "ABRT" command, which is sent from a client to a  
 15 server to abort a command, should always be processed asynchronously. The command includes the fields shown in the following table.

Addresses	Type	Contents
0004-0007	32-bit integer	Packet ID containing command.
0008-000B	32-bit integer	Offset of command chunk in packet, 0 if aborting entire packet.
000C	8-bit integer	0-abort the rest of the packet. 1-abort this command chunk and go on to the next command in the packet.
5 000D	8-bit integer	0-abort all successors to the command, reference "PRED" chunk 1-do not abort successors to the command.

A "LOAD" command loads data from a file into the server's memory. This should be the only way rules and examples are loaded from disk into the client or server - the client should not load rules in its own routines.

10

Addresses	Type	Contents
0004	8-bit integer	Type of data to load.
0005-0024	ASCIIIZ string	Symbolic name to give data, 32 characters.
0025-0125	ASCIIIZ string	Filename to load data from, 256 characters.

15 A "SAVE" command saves data from the server's memory to a file. Likewise, this should be the only way rules and examples are saved to disk from the client or server - the

client should not save rules in its own routines. The "SAVE" command has the fields listed below.

5

Addresses	Type	Contents
0004	8-bit integer	Type of data to save.
0005-0024	ASCIIIZ string	Symbolic name to save from, 32 characters.
0025-0125	ASCIIIZ string	Filename to save data to, 256 characters.

A "COPY" command, which includes the fields listed below, copies data from an area indicated by a symbolic name to another area in the server's memory.

10

Addresses	Type	Contents
0004	8-bit integer	Type of data to copy.
0005-0024	ASCIIIZ string	Symbolic name to copy from, 32 characters.
0025-0044	ASCIIIZ string	Symbolic name to copy to, 32 characters.

A "FREE" command, which includes the fields in the following table, frees a memory object in the server's memory.

Addresses	Type	Contents
0004	8-bit integer	Type of data to free.
0005-0024	ASCIIIZ string	Name of object, 32 characters.

A "GETD" command, which is used to get all default values, has no fields and returns a "DEFS" chunk. A corresponding "SETD" command is not needed because the client is able to send instead the "DEFS" chunk with any necessary modifications.

A "LIST" command, organized as shown below, lists all structures of the specified type and returns a "DIRS" chunk. The DIRS chunk tells the pieces that are currently in memory - rules, rulebases, examples, attributes, etc. If the type is set to zero, the command lists all structures.

Addresses	Type	Contents
0004	8-bit integer	Type of data to list.

The system also provides software functions such as the following.

15 `AdmireSendPacket(HWND hwndDest, LPSTR packetcontents, integer timeout)`

The function "AdmireSendPacket" asynchronously sends a packet and times out after the number of 10ths of a second indicated in the "timeout" field. The timeout procedure is necessary to avoid leaving the client in an endless loop if the server is inoperative, and vice versa.

The system also provides a handshaking procedure. The following describes the messages sent back and forth,

i.e., handshaking, that is performed to initiate communications, process commands, and terminate communications.

When a client wishes to initiate communication,  
5 i.e., begin using the rule engine server, it should first establish a connection with the server. This is done as indicated below by sending a series of "HELLO,n" control messages back and forth, where "n" is the LOWORD, i.e., low data word, of "lparam" for the HELLO message.

- 10 1. The client sends "HELLO,0" to all top-level windows, i.e., the main operating-system interfaces of applications, and waits for up to 3 seconds.
2. Each free, i.e., unattached, server responds with "HELLO,1" and then waits for a "HELLO,3" or  
15 "HELLO,4" response from the client. If the server receives a subsequent "HELLO,0" command from a different client, it queues that "HELLO,0" pending the response from the original client. Each busy, i.e., connected, server responds with "HELLO,2."
- 20 3. If the client receives at least one "HELLO,1" within the timeout period, it sends "HELLO,3" to the server

to which it intends to connect and "HELLO,4" to all other free servers which responded.

4. The server which received "HELLO,3" responds

"HELLO,2" to all subsequent "HELLO,0" commands,

5 because it is now attached to a client. Servers which received "HELLO,4" return "HELLO,1" until they are also attached to clients.

5. If the client times out while waiting for a response, it starts up another instance of the server application program and goes back to step 1.

10

When a client wishes to stop using a rule server, it should negotiate an end to the connection using the following process.

1. The client sends a "BYE" control message to the server.

15

2. The server cleans up in preparation for exit by releasing to the operating system the memory, fonts, bitmaps, and other system resources it is using and also by sending messages back to the client during this period which, e.g., warn of unsaved files.

20

3. The server sends "BYE" to the client and breaks the connection. Depending on the nature of the server, it exits or remains loaded as a free server.



4. The client breaks the connection.

The currently-used system uses a command-line interface. The following commands are used to produce the system's output.

```

5      LEARN rbname {
          var1 value1
          var2 value2
          ...
          LHS attr1
10      lhs attr2
          ...
          RHS attrn
15      }

```

The "LEARN" command learns a new rule base from examples and takes a list of parameters enclosed in brackets {}. Variables which are specified in capitals are mandatory; all others are taken from defaults if they are not present. Variable values are listed in pairs. There should be at least one attribute on the left-hand side and only one attribute on the right-hand side. The "}" bracket ends the parameter list for the "LEARN" command.

```

FILTER rbname filtertype value

```

25 The "FILTER" command filters the rule base with the types of filters listed and described below.

5                    ALWAYS attr  
                  NEVER attr  
                  ONLY attr  
                  PROB f  
                  LITTLEJ f  
                  PRIO f  
                  WEIGHT f  
                  LOWPROB f

10            The "ALWAYS" filter removes rules which do not  
             contain the specified attribute on the left-hand side.  
             Conversely, the "NEVER" filter removes rules which do  
             contain the specified attribute on the left-hand side. The  
             "ONLY" filter removes rules which have anything other than  
             the specified attribute on the left-hand side.

15            The remainder of the filters listed above address  
             threshold levels specified separately by "f." The "PROB"  
             filter removes rules with an insufficient probability of  
             being correct. Likewise, the "LITTLEJ," "PRIO," and  
             "WEIGHT" filters remove rules wherein the J-measure,  
20            priority, and weight, respectively, are too low. Finally,  
             the "LOWPROB" filter removes rules with an excessive  
             probability of being correct.

25            The "LOWPROB" filter is used to split a rule base  
             into two rule bases, one with high-probability rules and the  
             other with low-probability rules. For example, the  
             following steps can be performed using a set of rules "R1."

1. Copy R1 to Rhi.
2. Copy R1 to Rlo.
3. Filter Rhi with PROB 0.5.
4. Filter Rlo with LOWPROB 0.4999999.

5 The result is that rule base "Rhi" contains all of the high-probability rules and "Rlo" contains all of the rules of rule base "R1" that are not in rule base "Rhi." Moving the low-probability rules to a separate rule base eases analysis of them to determine whether they contain useful  
 10 information.

PRUNE rbname

The "PRUNE" command uses subsumption pruning to remove unneeded rules from the rule base.

RBLIST rbname{

15 rulebase1 flags1  
 rulebase2 flags2  
 ...  
 }

The "RBLIST" command creates a rule base list from  
 20 the specified rule bases and applies the rule bases in proper order using the specific flags. The rule base list should contain at least one rule base and flags should be separated by vertical bars "|," e.g., "ALLLHS|GUESS."

The allowed flags have the following meanings. Flag "ALLLHS," if set, indicates that the system should have values for all of the LHS attributes in the rule base before applying the rule base. A set "GUESS" flag forces the system to guess the most likely RHS if no rules fire. If the "OVERWRITE" flag is set, the system determines a new RHS value even if the current RHS value is known. Output data from each inference is kept if the "KEEPOD" flag is set. Finally, a set "RANDOM" flag indicates that if more than one RHS value is possible, one should be picked randomly based on the probabilities of the values.

TEST name WITH exlist

The "TEST" command tests the rule base or rule base list with the example set and prints the test statistics. Testing a rulebase with a set of examples involves, for each example in turn, comparing the expected result from the example with the predicted result from the rulebase.

The "TEST" command then prints out statistics such as those in the illustration below.

20	Total examples:	3134
	Examples classified:	3070 (98%)
	Examples classified correctly:	1477 (48%)
	Histogram of examples vs. rules fired per example:	

	Rules	Examples
	0	64
	1	6
	2	53
5	3	50
	4	108
	5	210
	6	252
	7	363
10	8	454
	9	395
	10	302
	11	305
	12	239
15	13	198
	14	61
	15	45
	16	25
	17	2
20	18	2

Average rules per example: 8.551

Histogram of examples vs. popularity of right answer:

Place	Examples	Avg. Rules
-------	----------	------------

1	1477	8.793
2	597	8.625
3	235	9.311
4	147	10.374
5	44	10.727
6	9	11.111

No rules predicted correct RHS: 625 0.000

In this illustration, the rule base was tested with a set of 3134 examples. If no rules fire, the rulebase does not make a classification. In 3070 of the examples, at least one rule fired. In 1477 of the examples, the rule base correctly classified the example.

The next section of the analysis shows a histogram of the number of rules fired. The histogram peaks at 8 rules per example and has an average of 8.551 rules per example.

The last section shows details about how successfully the rule base chose or at least suggested the correct answer. In 1477 of the examples, the rule base chose the correct answer. In 597 of the examples, the rule base selected the correct answer as the second-most-likely answer. In 625 of the examples, the rule base did not even suggest the correct answer as a possible answer.

The following describes commands relating to real-time inferencing.

```
INDATA idname {      (*Process for setting attributes
                        from other attributes *)
5   attr1 FROM attr2
   attr2 UNKNOWN
   attr3 TO val
   IF attr1 val1 THEN attr2 from attr3
}
```

10 The "INDATA" command creates the input data and should have at least one attribute-value pair. All values are initially set to a value of "UNKNOWN." For each attribute, the command gets its next value according to the following procedure in this example. First, the value of  
15 attribute "attr1" is copied from attribute "attr2." Next, attribute "attr2" is set to "UNKNOWN." Then attribute "attr3" is set to the specified value "val." Finally, the value of attribute "attr2" is copied from the value of attribute "attr3" only if attribute "attr1" has the value  
20 "val1."

The values "val" and "val1" are explicitly specified. For example, in a harmony "INDATA," the following setting is made at the start of each timestep.

Function0 UNKNOWN

25 Such a setting is equivalent to the following.

Function0 TO "?"

The "TO" operator can also be used to test a rule base which has more flexibility than is necessary at the moment. For instance, if a rulebase has rules for both  
5 major and minor keys, the following setting can be made to restrict use to the rules for the major key only.

MajMin TO Major

To ensure that an attribute's value is updated only under certain conditions, a directive such as the following  
10 can be used.

IF Accent1 ACC THEN FunctionLA from Function1

This directive copies the value from the previous timestep's function "Function1" into the previous accented beat's function "FunctionLA" only if the previous timestep was  
15 accented, i.e., "Accent1" had the value "ACC."

```
REALTIMEMIDI {  
    rblist  
  
    indata idname  
}
```



The "REALTIME MIDI" command harmonizes a melody in real time and expects the input data to contain the following attributes: Melody0, Function0, Inversion0, Alto0, and Tenor0. The rule base list to use, if not the default, is specified by "rblist." Likewise, the input data to use, if not the default data, is specified by applying the "indata."

NEW type name n

The "NEW" command creates a new empty structure capable of holding n elements, e.g., "NEW RBLIST simpleharm 16." Rule base lists are composed of rule bases which in turn are composed of rules. Likewise, example lists are composed of examples and attribute bases are composed of attributes.

15 JOIN name AND name INTO name

The "JOIN" command allows two rule bases to be merged to create a new rule base.

#### F. Other Embodiments

The embodiments described above are but examples, which can be modified in many ways within the scope of the appended claims. For example, the invention can also use

accent-based conversion, wherein additional example fields are allowed to be created for previous timesteps which start at the beginning of a beat, accented beat, or fermata. In accent-based conversion, only one example is created per timestep, so it is not necessary to weight the examples, a list of which would likely appear as follows.

```

%NAME 0 FunctionLastAccentedBeat
%NAME 1 FunctionLastBeat
%NAME 2 Function1
10 %NAME 3 Function0
-      -      -      I
-      I      I      I
I      I      I      IV
I      IV     IV     vi
15 I      IV     vi     V

```

With accent-based conversion, it is possible for the first three fields to refer to the same timestep if the previous timestep was at the start of an accented beat. Such redundancy, which leads to highly interdependent rules, makes real-time independence pruning essential.

Furthermore, the invention can use non-MIDI input sources, such as pitch data from a microphone, allowing a vocalist to sing or hum a tune which is converted into pitches and used to generate a harmony. Likewise, the invention can accept pitch data from a program, such as a

program according to the invention which generates melodies instead of harmonies.

In addition, the invention can be applied to assist in the derivation of a representation for the overall  
5 structure of a piece of music by encoding information about phrases and sections in music, such as the verse-chorus structure common to much vocal music. The invention can also provide a system which includes cues for modulation from one key to another.

10 In addition, the invention can provide a system allowing voices to make jumps over awkward intervals such as tritones or over distances further than an octave. Furthermore, the invention can provide a system realizing a figured bass that allows two voices to cross or to play in  
15 unison, i.e., play the same pitch. The invention can also provide a system that develops information about whether voices are changing pitch in the same or different direction as other voices.

Moreover, the invention can provide a system that  
20 detects ornaments, described above, which are usually used to smooth a voice line by removing large jumps in pitch. The invention can add such ornaments to generated harmonies to make them more interesting.

Furthermore, the invention can provide a system relating to drums and other percussion instruments, by using a notation for rhythm.

In addition, the invention can provide a system  
5 relating to orchestration and part writing in the areas of music involving expansion of four-part harmony into sufficient additional lines so that each instrument in an orchestra has something interesting to play, in the pitch range which the instrument can generate. The invention can  
10 also assist in research focusing on the methods used to duplicate and modify voice lines to produce distinct parts, and ways of moving the melody between instruments.

Likewise, the invention can provide a system relating to similar concepts needed to reproduce  
15 contemporary music, wherein the harmonic information is distributed between a vocalist, lead guitar, bass guitar, keyboard player, and other instruments.

In addition, the invention can use Bach inventions, sinfonias, and fugues to learn rules for counterpoint and  
20 development of a theme or motive. Similarly, the invention can assist in the study of methods for employing chord accents in syncopated rhythms to provide extracts from ragtime pieces by Scott Joplin, for instance. Furthermore,

the invention can use, for example, African drum music or any other sound to develop rhythm notation.

Moreover, the invention can assist in research focusing on the differences between the styles of various composers to determine, e.g., what makes Mozart piano sonatas sound different than Beethoven piano sonatas, and how the choral works of Bach differ from those of Handel.

Other embodiments:

-Extending Temporal Knowledge

Existing rulebase sets look only at the accent of the current chord and the information from the previous few chords. This limits the ability of the rulebases to compensate for and generate harmonic transitions on a larger scale.

Deriving a representation for the overall structure of a piece of music would allow ADMIRE additional flexibility in this regard. Such a representation would encode information about phrases and sections in music, such as the verse-chorus structure common to much vocal music. It would also include cues for modulation from one key to another.

- Counterpoint and Voice Leading

Although the existing voice position rules perform an acceptable job of filling in the pitches used by a given chord, they do little to make the individual voices singable. Voices often have jumps over awkward intervals such as tritones or distances over an octave. Furthermore, the current method for realizing a figured bass does not allow two voices to play a unison (play the same pitch), nor does it allow voices to cross. It also lacks information about whether voices are changing pitch in the same or different direction as other voices.

Additional adding of ornamentation can be used to smooth a voice line by removing large jumps in pitch. Once ornaments are well understood, they could also be added to generated harmonies to make them more interesting.

### 6.3 Rhythm Notation and Percussion

Most contemporary music includes drums and other percussion instruments. Drum parts tend to change on a measure-by-measure basis, and an entire piece of music may contain relatively few distinct drum patterns which are combined in various orders. In addition, most percussion sounds are to a large extent atonal; the information contained in their parts is almost entirely rhythmic. These

differences will necessitate a notation for rhythm that is much different than the pitch-based or chord-based representations currently used in ADMIRE>

#### - Orchestration and Part Writing

5       Orchestration and part writing are the areas of music involving expansion of four-part harmony into sufficient additional lines so that each instrument in an orchestra has something interesting to play, in the pitch range which the instrument can generate. Research here could focus on the  
10       methods used to duplicate and modify voice lines to produce distinct parts, and ways of moving the melody between instruments.

#### - Different Forms of Music

      Once the rules of Bach chorales are well understood,  
15       research could be expanded to encompass other musical forms. Bach inventions, sinfonias, and fugues could be used to learn rules for counterpoint and development of a theme or motive. Methods for employing chord accents in syncopated rhythms could be extracts from ragtime pieces by Scott  
20       Joplin. Rhythm notation could be developed on African drum music. Orchestral works by Mozart and Haydn could be used

as examples for part writing and orchestration, with Beatles music serving in a similar role for contemporary music.

Research could also focus on the differences between the styles of various composers. What makes Mozart piano sonatas sound different than Beethoven piano sonatas, and how do the choral works of Bach differ from those of Handel? Since the algorithms used are all rule-based, it is possible to investigate the rules which are generated and how they are fired.

10       All of these modifications are intended to be encompassed within the following claims, in which:



What is claimed is:

1. A method of composing music, comprising:

receiving a first series of musical notes defining a  
5 first melody having a first harmony;

analyzing the first harmony within the first melody,  
by forming examples from the first series of musical notes,  
and deriving, in real-time, at least first and second rules  
relating to the first melody, the second rule conflicting  
10 with the first rule, and each of said first and second rules  
including a weight associated therewith;

receiving additional notes of said melody and  
forming additional examples from said additional notes;

determining ones of said additional examples that  
15 agree with said first rule and increasing a weight of said  
first rule when an example agrees with said first rule, and  
determining ones of said additional examples that agree with  
said second rule and increasing a weight of said second rule  
when an example agrees with said second rule;

20 receiving another melody to which a harmony is to be  
formed;

evaluating said another melody using both of said first and second rules; and

when both said first and second rules each apply to said another melody, applying the one of said rules which  
5 has the higher weight to said melody, in real-time.

2. The method of claim 1 further comprising analyzing the first harmony to derive in real-time a second rule relating the first melody to first harmony, the second rule conflicting with the first rule;

10 comparing the first rule to the second rule; and  
assigning a weight to an outcome of the second rule;  
and

choosing an outcome based on the weights.

3. A method of analyzing musical information,  
15 comprising:

converting the musical information from MIDI format to figured bass format;

generating an example table from the figured bass musical information; and

determining a plurality of rules, each rule determined from two distinct examples within said example table, which are different than one another, one property of each rule relating to statistics of musical information in  
5 the examples.

4. The method of claim 3, further comprising applying filtering, segmentation, and subsumption pruning to the rule; and generating dependency data using the rule.

10 5. The method of claim 3, wherein deriving a rule using the example table comprises calculating a hash value for an example; forming a preliminary rule linking the hash value to an attribute to be inferenced; and  
15 subjecting the preliminary rule to a quality test.

6. The method of claim 5, further comprising: calculating hash values for a plurality of examples; and

wherein the subjecting comprises rejecting the preliminary rule if an insufficient quantity of examples correspond to the preliminary rule's hash value.

5           7.    The method of claim 5, further comprising:  
calculating hash values for a plurality of examples;  
and

the quality test comprises rejecting the preliminary rule if the preliminary rule's hash value corresponds to an  
10 insufficient quantity of examples having a particular value of the attribute to be inferenced.

8.    The method of claim 5 further comprising  
calculating a J-measure for the preliminary rule,  
wherein

15           the quality test comprises rejecting the preliminary rule if the preliminary rule's J-measure is insufficient.

9.    The method of claim 4 wherein the rule is filtered out if the rule disregards a current melody note in determining a chord function.

20           10. The method of claim 4 further comprising

deriving a plurality of rules;  
organizing the rules in a rulebase; and  
segmenting the rulebase into a plurality of new  
rulebases; wherein

5           a first new rulebase includes rules having a  
desired attribute; and

          a second new rulebase includes rules lacking  
the desired attribute.

11. A method of producing a database of rules for  
10   producing musical sounds, comprising:

          using first musical sounds as examples to derive a  
plurality of rules;

          organizing the rules in a rulebase; and

          removing a first rule from the rulebase if:

15           the first rule and a second rule predict a same  
value of a same attribute,

          the first rule has more attributes than the  
second rule,

          all of the attributes of the first rule are  
20   present with substantially the same values in the second  
rule, and

the second rule is correct at least as often as the first rule.

12. The method of claim 11 further comprising determining that two rules are dependent if both  
5 rules are activated in at least half of the instances in which at least one of the two rules is activated.

13. A music composition system comprising  
an analyzer receiving a first harmony including a first melody and deriving in real-time a first rule relating  
10 the first melody to the first harmony; and  
a harmonizer receiving a second melody and applying the first rule in real-time to the second melody to produce a second harmony relating to the second melody.

14. A music composition system comprising  
15 an analyzer receiving a first harmony including a first melody and deriving in real-time a first rule relating the first melody to the first harmony and a weight for the first rule based on statistical information in the first melody and first harmony, wherein the analyzer derives a  
20 second rule in real-time relating the first melody to first

harmony and a weight for the first rule based on statistical information, the second rule conflicting with the first rule; and

5 a harmonizer receiving a second melody and applying the first rule in real-time to the second melody to produce a second harmony relating to the second melody,

said harmonizer comparing the first rule to the second rule and determining which of said rules to use based on said weights.

10 15. A method of converting musical information of a musical piece from MIDI format to figured bass format, comprising

transposing the musical piece to a standard key;

segmenting the transposed musical piece into chords

15 by beginning a new chord whenever a voice changes pitch;

attempting to match each chord with a known chord to produce identified chords each having a root and a type;

determining a position for each voice of each identified chord by comparing each voice's pitch with  
20 pitches allowed in the voice's matching known chord; and

attempting to match each identified chord with a known function by comparing each identified chord's root and type with a table of common functions.

16. A musical information analyzer, comprising  
5 a converter receiving musical information in MIDI format and producing musical information in figured bass format;

a table generator deriving an example table from the figured bass musical information; and

10 a rule generator, determining a plurality of rules, each rule determined from the two distinct examples which are different than one another, one property of each rule relating to statistics of musical information in the examples.

15 17. The analyzer of claim 16, further comprising  
a filter applying filtering to the rule;  
a rule segmenter applying segmentation to the rule;  
a pruner applying subsumption pruning to the rule;  
and

20 a dependence analyzer generating dependence data using the rule.



18. The analyzer of claim 16, wherein the rule generator comprises:

a hash calculator calculating a hash value for an example;

5 a preliminary rule generator forming a preliminary rule linking the hash value to an attribute to be inferenced; and

a tester subjecting the preliminary rule to a quality test.

10

19. The analyzer of claim 18, wherein

the hash calculator calculates hash values for a plurality of examples; and

15 the quality test comprises rejecting the preliminary rule if an insufficient quantity of examples correspond to the preliminary rule's hash value.

20. The analyzer of claim 18, wherein

20 the hash calculator calculates hash values for a plurality of examples; and

the quality test comprises rejecting the preliminary rule if the preliminary rule's hash value corresponds to an

insufficient quantity of examples having a particular value of the attribute to be inferred.

21. The analyzer of claim 18 further comprising  
a J-measure calculator calculating a J-measure for  
5 the preliminary rule, wherein  
the quality test comprises rejecting the preliminary  
rule if the preliminary rule's J-measure is insufficient.

22. The analyzer of claim 17 wherein the filter  
removes the rule if the rule disregards a current melody  
10 note in determining a chord function.

23. The analyzer of claim 17 wherein  
the rule generator derives a plurality of rules;  
a rule organizer organizes the rules in a rule base;  
and  
15 the rule segmenter segments the rule base into a  
plurality of new rule bases; wherein  
a first new rule base contains rules having a  
desired attribute; and  
a second new rule base contains rules lacking the  
20 desired attribute.

24. The analyzer of claim 17 wherein:  
the rule generator derives a plurality of rules;  
a rule organizer organizes the rules in a rulebase;  
and  
5 the pruner removes a first rule from the rulebase  
if:  
the first rule and a second rule predict a same  
value of a same attribute,  
the second rule has more attributes than the  
10 first rule,  
all of the attributes of the first rule are  
present with the same values in the second rule, and  
the second rule is correct at least as often as  
the first rule.
- 15 25. The analyzer of claim 17 wherein  
the rule generator derives a plurality of rules; and  
the dependence analyzer determines that two rules  
are dependent if said two rules are activated in at least  
half of the instances in which at least one of the two rules  
20 is activated.

Kindly add the following new claims:

26. A system which converts musical information of a musical piece from MIDI format to figured bass format, comprising

5 a key transposer transposing the musical piece to a standard key;

a segmenter segmenting the transposed musical piece into chords by beginning a new chord whenever a voice changes pitch;

10 a chord matcher attempting to match each chord with a known chord to produce identified chords each having a root and a type;

a position determiner determining a position for each voice of each identified chord by comparing each  
15 voice's pitch with pitches allowed in the voice's matching known chord; and

a function matcher attempting to match each identified chord with a known function by comparing each identified chord's root and type with a table of common functions.

27. A method of composing music, comprising:  
obtaining a sample of music whose style is to be analyzed;  
producing a plurality of examples from said sample of music;

generating a plurality of rules from the plurality of examples, said rules predicting certain examples which follow other examples, and each said rule including weights associated therewith, said weights defining a statistical likelihood that said rule will be followed,

increasing a weight of a rule when a particular example agrees with the rule; and

decreasing a weight of the rule when a particular example does not agree with the rule.

28. A method as in claim 27 further comprising:  
storing all of said rules into a rulebase;  
obtaining a melody which is to be analyzed using said rules in said rulebase; and

analyzing said melody using all of said rules in said rulebase, by using said melody to fire all rules in said rulebase which are applicable to said melody, evaluating a result of firing of said rules, and resolving

conflicts between conflicting rules based on said weights associated with the conflicting rules.

29. A method as in claim 28 wherein said rules relate to harmonies that are derived from melodies, and further comprising:

presenting a harmony produced by a particular rule to an operator who can determine if said harmony is desirable;

accepting an input from said operator indicating if said harmony is desirable;

increasing the weight for the particular rule if the harmony is desirable and decreasing the weight for the particular rule if the policy is not desirable.

30. A method of generating rules from a musical piece, comprising:

obtaining musical information;

converting said musical information to examples;

determining a minimum number parameter, indicating a minimum number of agreements before a rule can be formed;

comparing said examples to generate a prediction of attributes that will follow one another;

determining if each said prediction has occurred before within said set of examples by a number of times

having a predetermined relationship with said minimum number parameter;

establishing a rule of the form "If (a) Then (b)" if said prediction has occurred said number of times having said predetermined relationship with said minimum number parameter; and

establishing a weight associated with said rule, said weight indicative of a number of times that (a) correctly predicts (b).

31. A method as in claim 30 wherein said rule is of the form "If attribute (A1) and attribute (A2) Then attribute (B3); correct X percent of the time, where x is the percentage of times that attributes (A1) and (A2) predict attribute (B3).

32. A method as in claim 27, further comprising ordering said database in a way that improves use of said rules.

33. A method as in claim 32, wherein said ordering comprises

determining a certain attribute which is important for a current application; and

filtering the plurality of rules to prevent rules from being used which do not use that attribute.

34. A method as in claim 33 wherein said attribute is a rule which disregards a current melody note in determining a current chord function.

35. A method as in claim 32, wherein said ordering comprises

determining a desired attribute for a desired application;

grouping the plurality of rules based on whether they include that desired attribute;

placing rules which include the desired attribute in a first segmented rulebase, and placing rules which do not include the desired attribute into a second unsegmented rulebase.

36. A method as in claim 35 further comprising:  
obtaining a musical melody to be applied to said database;

first checking said segmented rulebase to determine if rules in said segmented rulebase meet a predetermined criteria and if so, using only the rules in said segmented rulebase; and



if no rules meet the predetermined criteria, using the rules in said unsegmented rulebase.

37. A method as in claim 36 wherein the predetermined criteria is whether a rule has fired.

38. A method as in claim 27, further comprising analyzing the rules to determine rules which are depending with other rules; and

removing at least some of the dependent rules.

39. A method as in claim 38 wherein said analyzing comprises:

finding at least two rules which produce a same result;

determining a set of examples for which each rule fires;

determining an overlap for which both rules fire; and

determining a percentage of dependence between the rules.

40. A method of composing music, comprising:  
obtaining a sample of music whose style is to be analyzed;

producing a plurality of examples from said sample of music;

generating a plurality of rules from the plurality of examples, said rules predicting certain examples which follow other examples, and each said rule including weights associated therewith, said weights defining a statistical likelihood that said rule will be followed;

storing all of said rules into a rulebase;

analyzing a melody which using said rules in said rulebase to form a harmony accompanying said melody to provide an accompaniment to said melody according to said rulebase;

listening to said accompaniment; and

either taking no action based on said accompaniment in which case a weight which produced the harmony is unchanged, taking an action to indicate dislike of the result in which case said weight which produced the harmony is decreased, or taking an action to indicate like of the result in which case said weight is increased.

41. A method as in claim 40 wherein said increase in weight is by .01.

42. A method as in claim 1, wherein said first and second rules are increased in weight each time an example agrees.

43. A method as in claim 1, wherein there are more than two rules formed by said analyzing, said more than two rules form a rulebase, and wherein all of said rules in said rulebase are evaluated during said evaluating.

44. A system as in claim 14, wherein there are more than two rules formed by said analyzer, said more than two rules form a rulebase, and wherein all of said rules in said rulebase are evaluated by said analyzer.

45. A method of composing music, comprising:  
obtaining a sample of music whose style is to be analyzed;  
producing a plurality of examples from said sample of music;  
generating a plurality of rules from the plurality of examples, said rules predicting certain examples which follow other examples, and each said rule including weights associated therewith, said weights defining a statistical likelihood that said rule will be followed;  
storing all of said rules into a rulebase;

using said rulebase to analyze another melody, by evaluating taking all of the plurality of rules in the rulebase in parallel and then resolves any conflicts between rules based on the rule weights. 1. A method of composing music, comprising

receiving a first series of musical notes defining a first melody;

analyzing the first harmony to derive in real-time at least two rules relating to the first melody;

receiving additional notes; and

applying the at least two rules in real-time to the additional notes, to generate chord notes that relate to the additional notes.

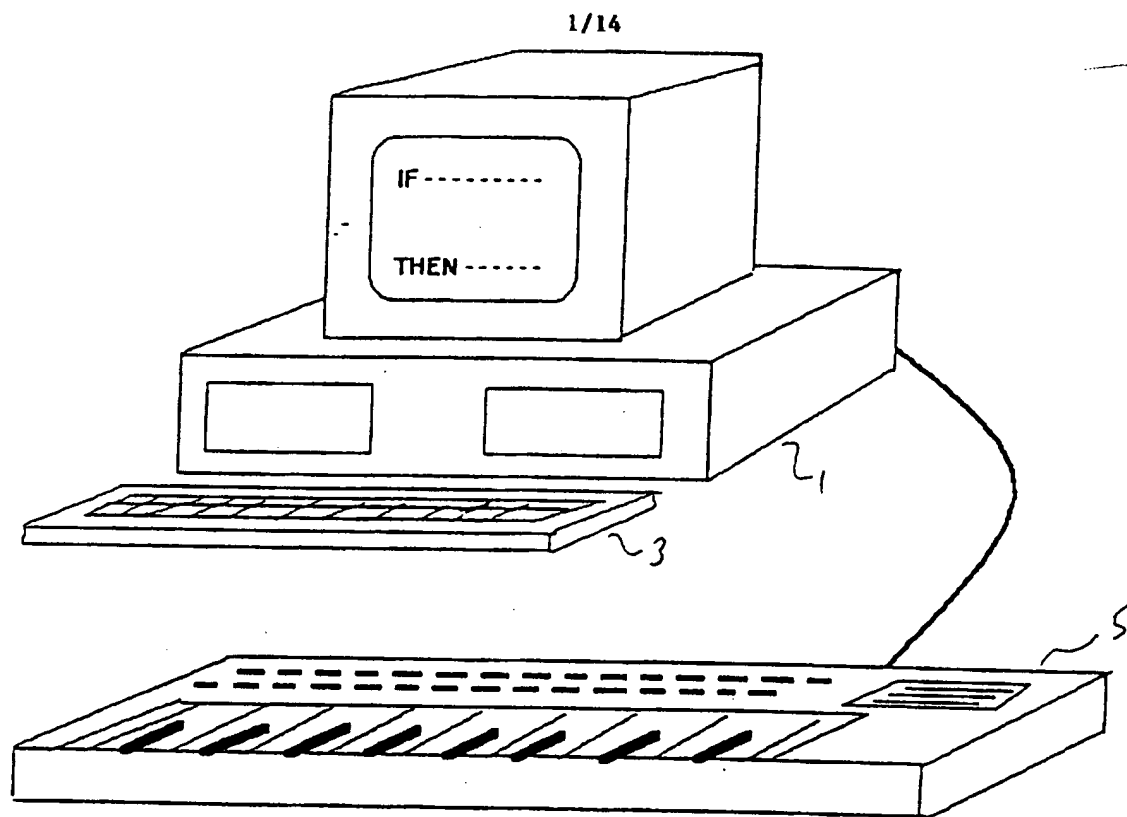


FIG. 1

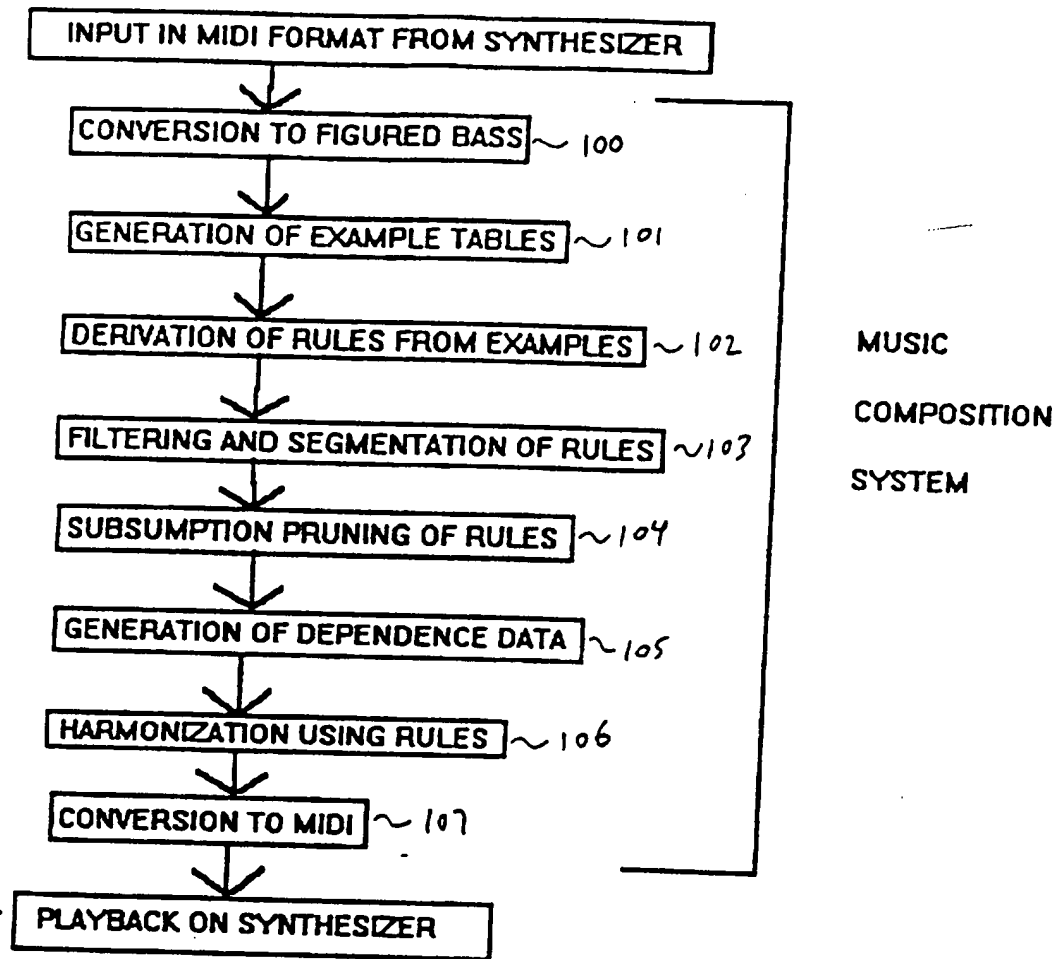


FIG. 2

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## CONVERSION TO FIGURED BASS

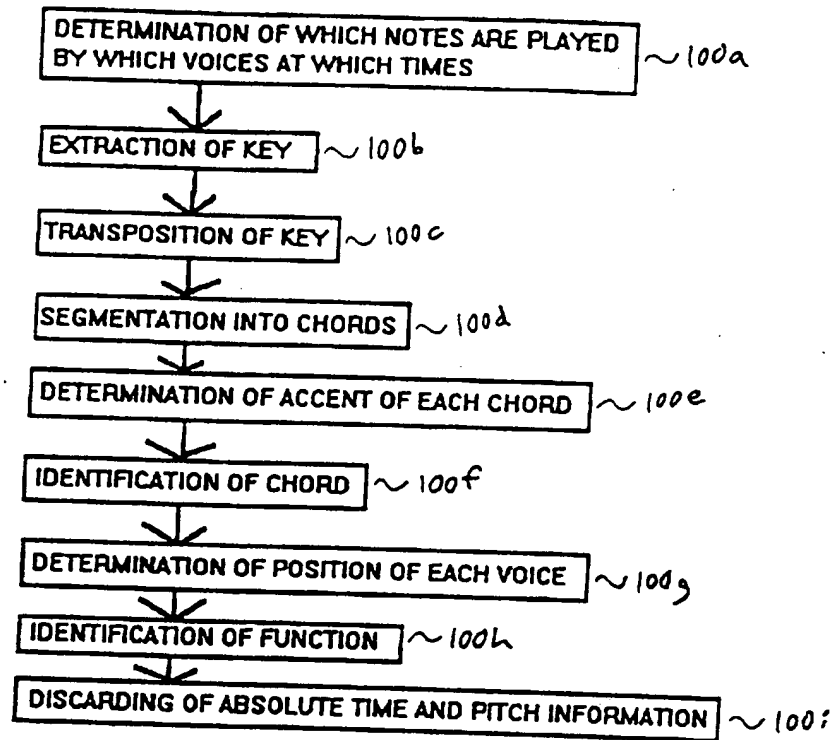


FIG. 3

$$J(X; Y = y) = p(y) \cdot [P(X|Y) \cdot \log\left(\frac{p(x|y)}{p(x)}\right) + (1 - p(x|y)) \cdot \log\left(\frac{(1 - p(x|y))}{(1 - p(x))}\right)]$$

FIG. 4



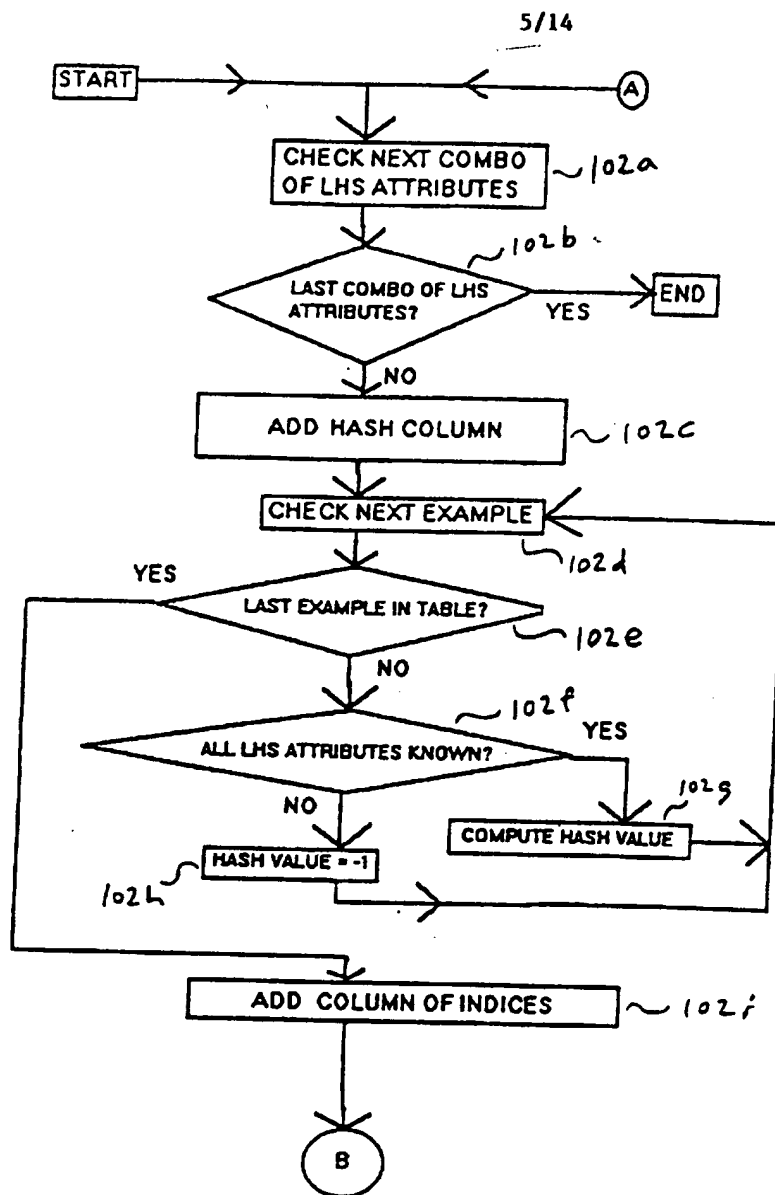


FIG. 5

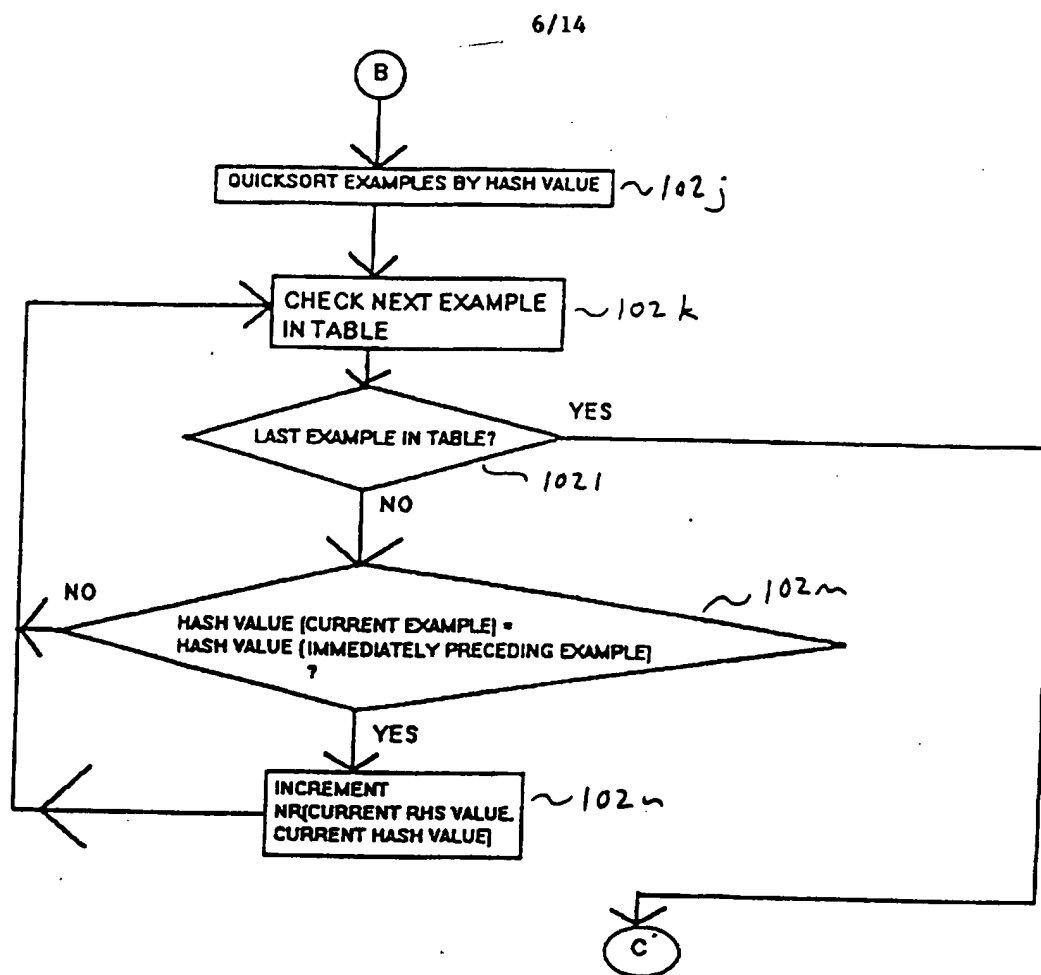
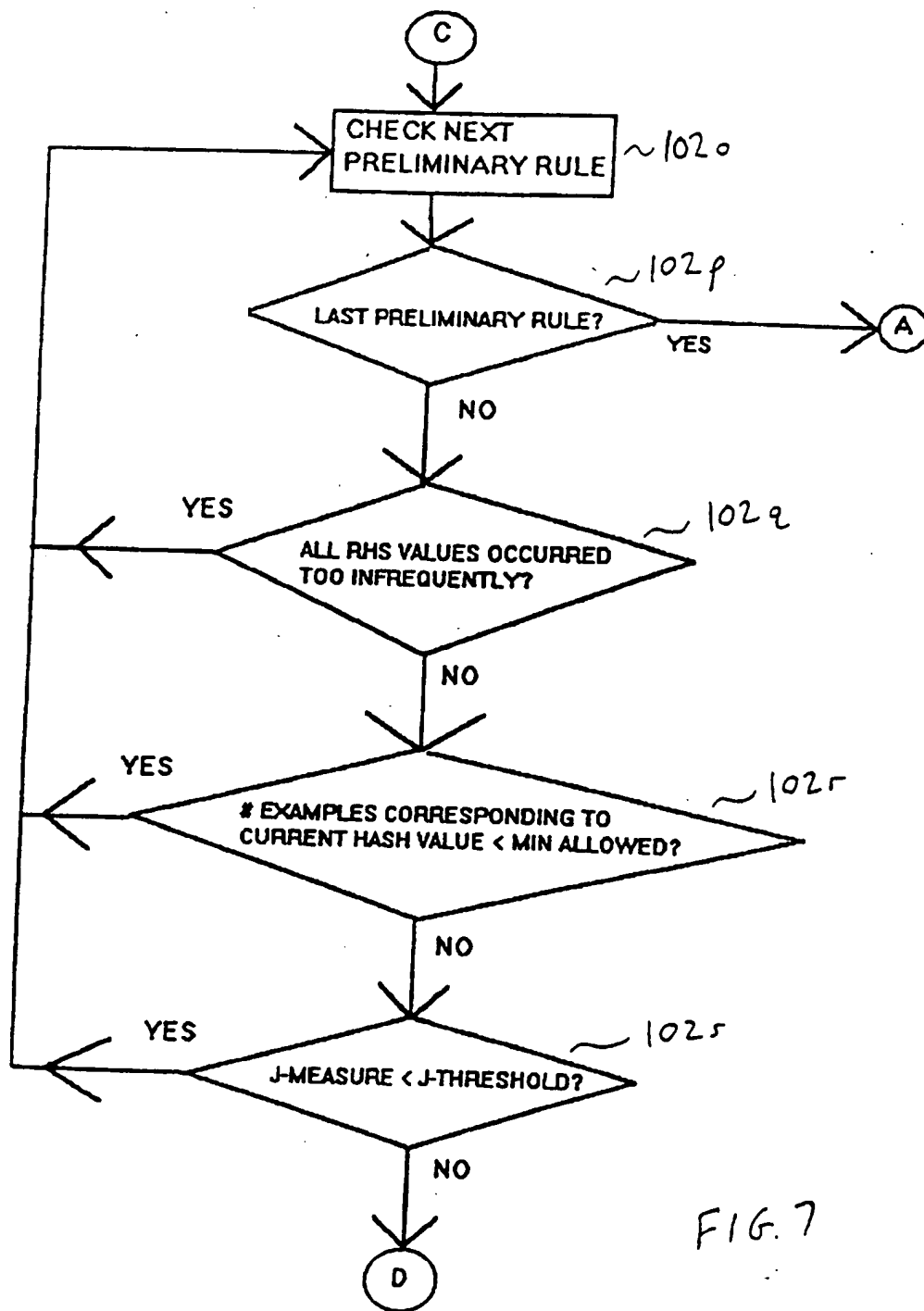


FIG. 6

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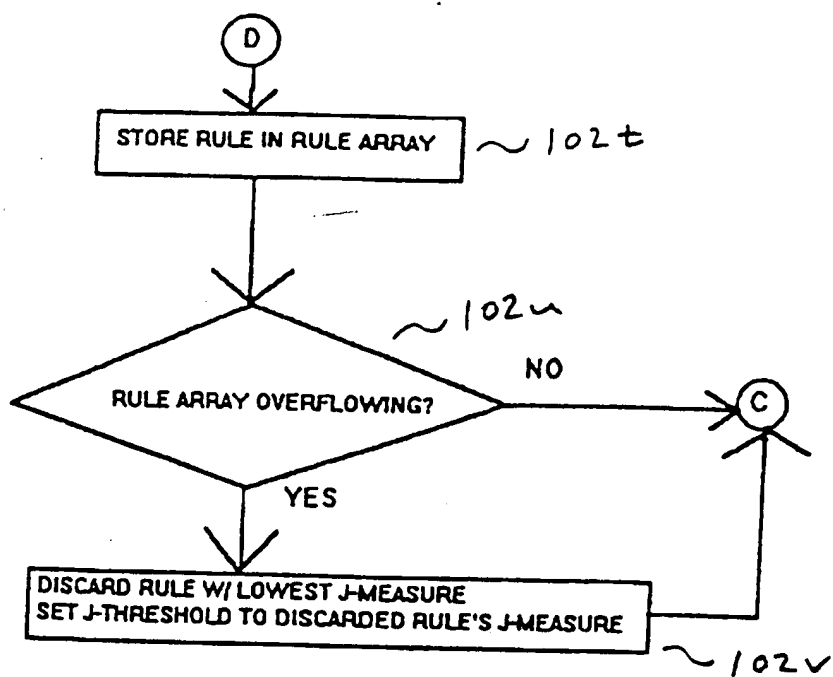


FIG. 8

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## HARMONIZATION USING RULES

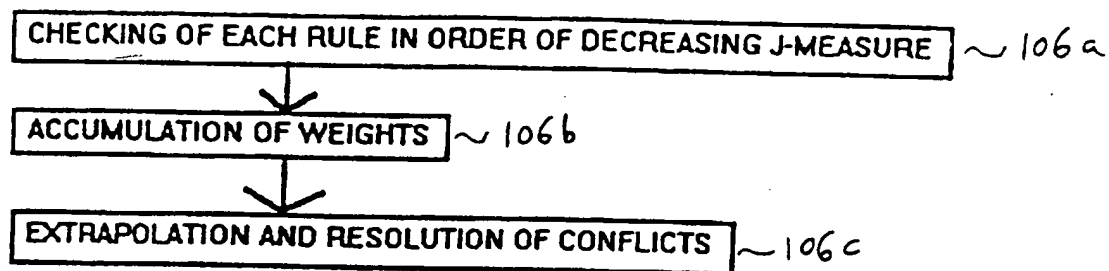


FIG. 9

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## CONVERSION TO MIDI

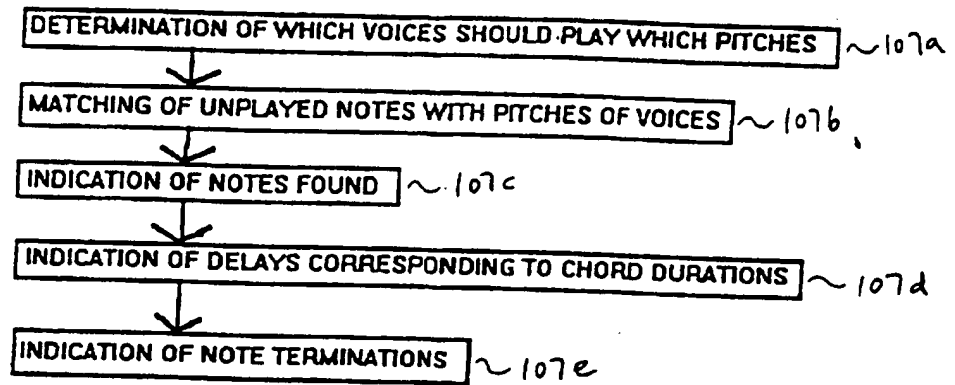


FIG. 10



FIGURE 11

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FIGURE 12





FIGURE 13

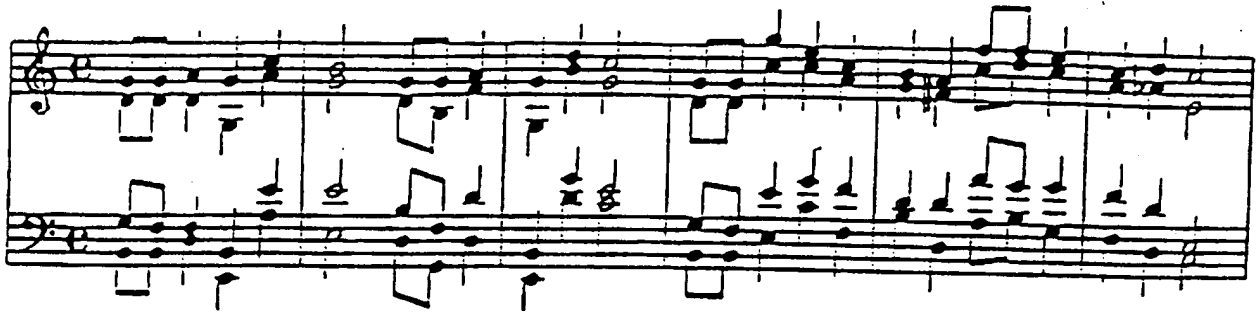


FIGURE 14

## INTERNATIONAL SEARCH REPORT

International application No.  
PCT/US97/04636**A. CLASSIFICATION OF SUBJECT MATTER**

IPC(6) :G10H 1/00, 7/00

US CL :84/634, 649, 650, 666, 669

According to International Patent Classification (IPC) or to both national classification and IPC

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 84/634, 649, 650, 666, 669, 635, 637, 651, 667, 669, DIG. 9

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)  
APS**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y --- A	US 5,218,153 A (MINAMITAKA) 08 JUNE 1993, COL. 11, LINES 6-36	3, 16 ----- 1-2, 4-15, 17-45
Y --- A	US 5,396,828 A (FARRAND) 14 MARCH 1995, COL. 3, LINES 61-68 AND COL. 37, LINES 1-5	3, 16 ----- 4-10, 14, 17-26
Y --- A	US 5,418,323 A (KOHONEN) 23 MAY 1995, COL. 2, LINES 8-15	3, 16 ----- 2, 14, 23-25

☐ Further documents are listed in the continuation of Box C.
 ☐ See patent family annex.

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